Photon production in heavy-ion collisions

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Electromagnetic probes: photons and dileptons

Feinberg (76), Shuryak (78)

Advantages:

✓ dileptons and real photons are emitted from different stages of the reaction and not effected by final-state interactions

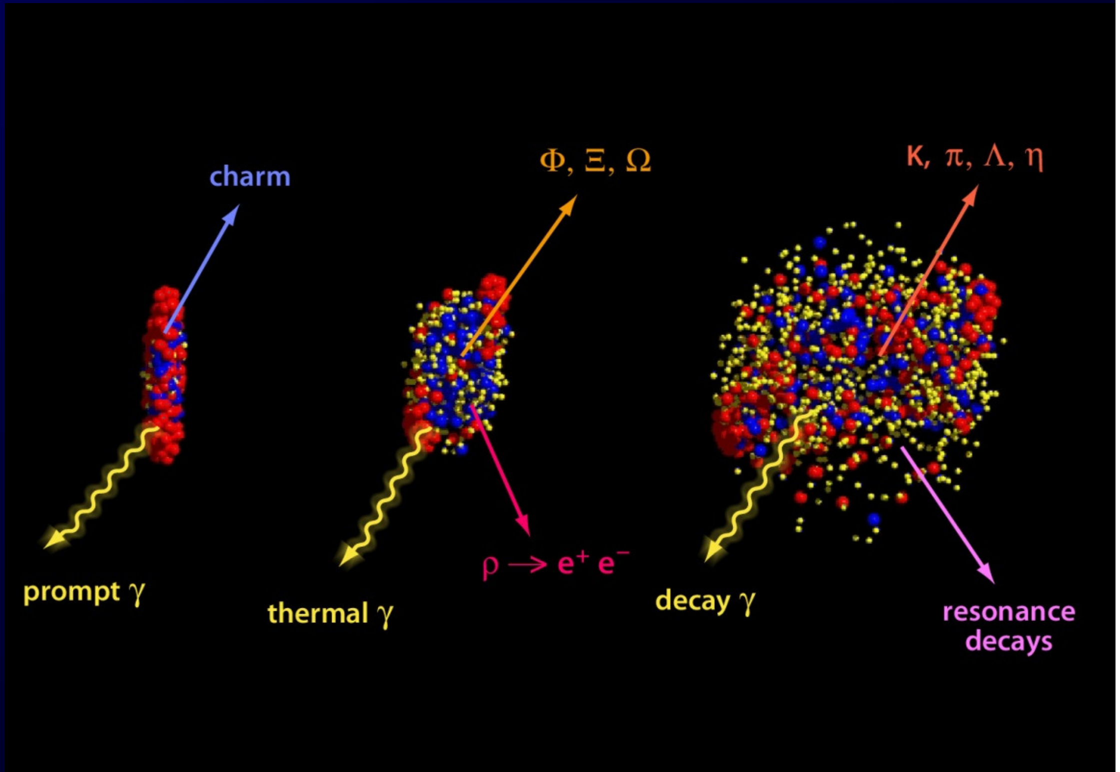
✓ provide undistorted information about their production channels

✓ promising signal of QGP – ‚thermal‘ photons and dileptons

➔ Requires theoretical models which describe the dynamics of heavy-ion collisions during the whole time evolution!

Disadvantages:

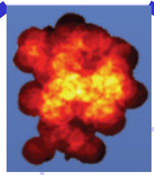
- low emission rate
- production from hadronic corona
- many production sources which cannot be individually disentangled in experimental data



Dynamical models for HIC

Macroscopic

hydro-models:
- description of QGP and hadronic phase by hydrodynamical equations for fluid
- assumption of local equilibrium
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)



ideal
(Jyväskylä,SHASTA, TAMU, …)

viscous
(Romachkke,(2+1)D VISH2+1, (3+1)D MUSIC,…)

fireball models:
- no explicit dynamics: parametrized time evolution (TAMU)

Microscopic

Non-equilibrium microscopic transport models – based on many-body theory

Hadron-string models
(UrQMD, IQMD, HSD, QGSM …)

Partonic cascades
pQCD based
(Duke, BAMPS, …)

Parton-hadron models:
- QGP: pQCD based cascade
- massless q, g
- hadronization: coalescence

(AMPT, HIJING)

PHSD
- QGP: lQCD EoS
- massive quasi-particles (q and g with spectral functions) in self-generated mean-field
- dynamical hadronization
- HG: off-shell dynamics

(applicable for strongly interacting systems)

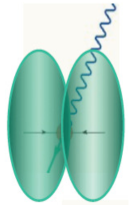
‚Hybrid'

QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

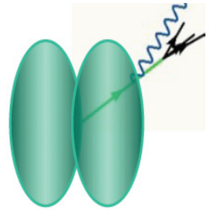
(‚hybrid'-UrQMD, EPOS, …)

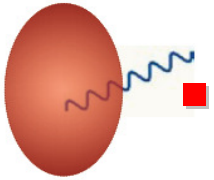
Production sources of photons in p+p and A+A

- **Decay photons** (in pp and AA):
  $m \rightarrow \gamma + X, \; m = \pi^0, \eta, \omega, \eta', a_1, \ldots$

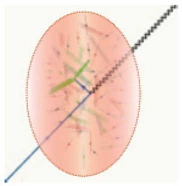


- **Direct photons:** (inclusive(=total) – decay) – measured experimentally
  - **hard photons**: (large p_T, in pp and AA)
    - **prompt** (pQCD; initial hard N+N scattering)
    - **jet fragmentation** (pQCD; qq, gq bremsstrahlung) (in AA can be modified by parton energy loss in medium)

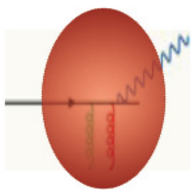




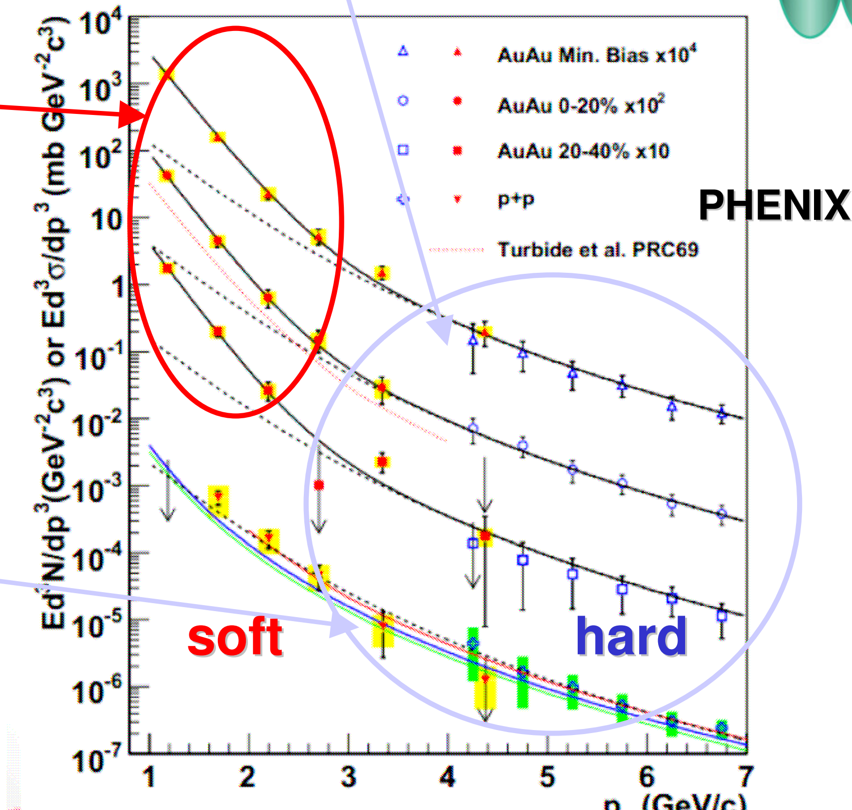
- **thermal photons**: (low p_T, in AA)
  - QGP
  - Hadron gas



- **jet-γ-conversion** in plasma (large p_T, in AA)



- **jet-medium photons** (large p_T, in AA) - scattering of hard partons with thermalized partons $q_{hard}+g_{QGP} \rightarrow \gamma+q$,
  $q_{hard}+qbar_{QGP} \rightarrow \gamma+q$

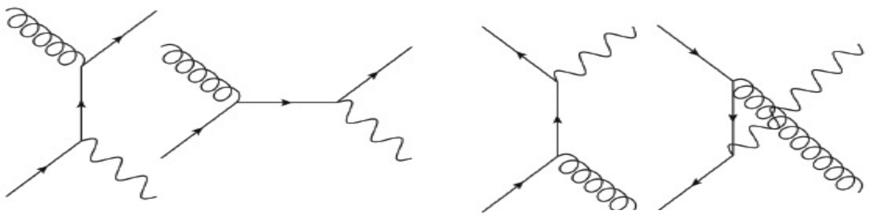


Phys. Rev. C 81, 034911 (2010)

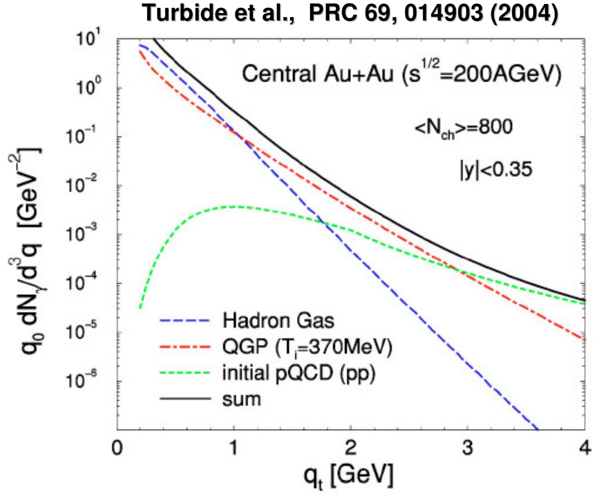
Production sources of thermal photons

Thermal QGP:

Compton scattering   q-qbar annihilation



$q(\bar{q}) + g \rightarrow q(\bar{q}) + \gamma$ $q + \bar{q} \rightarrow g + \gamma$ + soft …

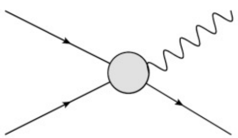


Photon rates from QGP:

- pQCD LO: 'AMY' Arnold, Moore, Yaffe, JHEP 12, 009 (2001) ← used in hydro !
- pQCD NLO: Gale, Ghiglieri (2014)
- resummed QCD: off-shell massive q, g O. Linnyk, JPG 38 (2011) 025105 ← used in PHSD

Hadronic sources:

(1)



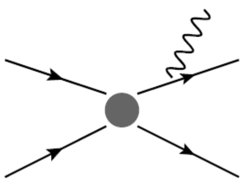
secondary mesonic interactions:

$\pi+\pi \rightarrow \rho+\gamma,\ \rho+\pi \rightarrow \pi+\gamma,\ \pi+K \rightarrow \rho+\gamma,\ \ldots$ TRG ← used in hydro

HG rates from massive Yang-Mills approach (TRG) Turbide, Rapp, Gale, PRC 69, 014903 (2004)

Effective Lagrangian cross sections Kapusta et al PRC 69, 014903 (2004) ← used in PHSD

(2)



meson-meson and meson-baryon bremsstrahlung:

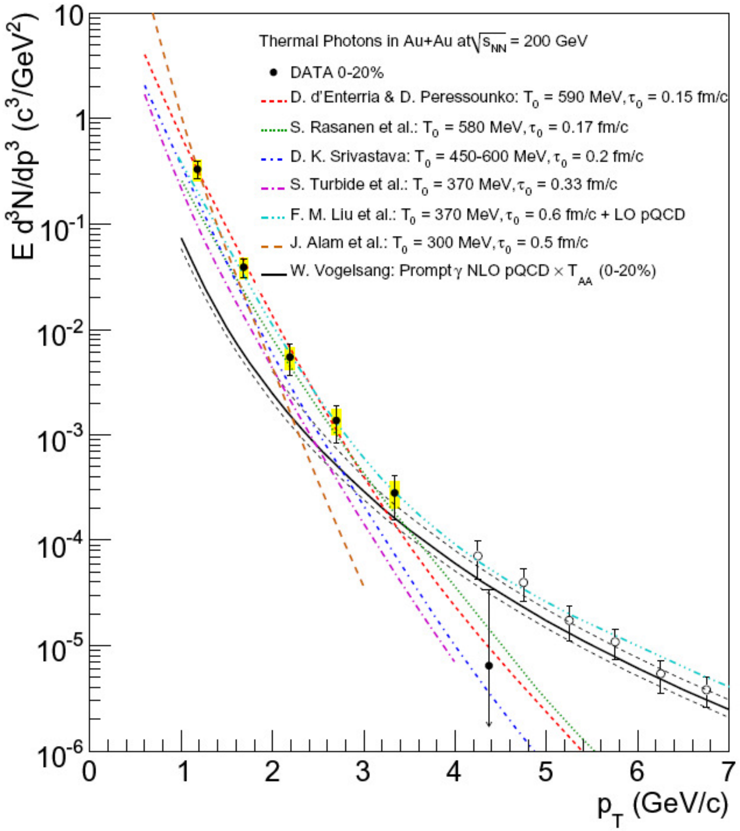
$m+m \rightarrow m+m+\gamma,\quad m+B \rightarrow m+B+\gamma,\ m=\pi,\eta,\rho,\omega,K,K^*,\ldots,\ B=p,\Delta,\ldots$

Models: chiral OBE, soft-photon approximation (SPA) … ← used in PHSD

2010: Direct photon spectra for Au+Au at $s^{1/2}$=200 GeV

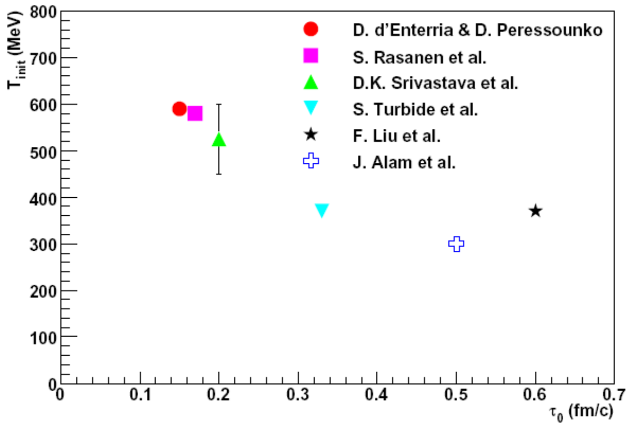
PHENIX, Phys. Rev. C81 (2010) 034911

Variety of model predictions:
fireball, 2+1 Bjorken hydro, 3+1 ideal hydro with different initial conditions and EoS



Models: assume formation of a hot QGP with initial temperature T_{init} at thermalization time τ_0

➔ Huge variations in T_{init} and τ_0!

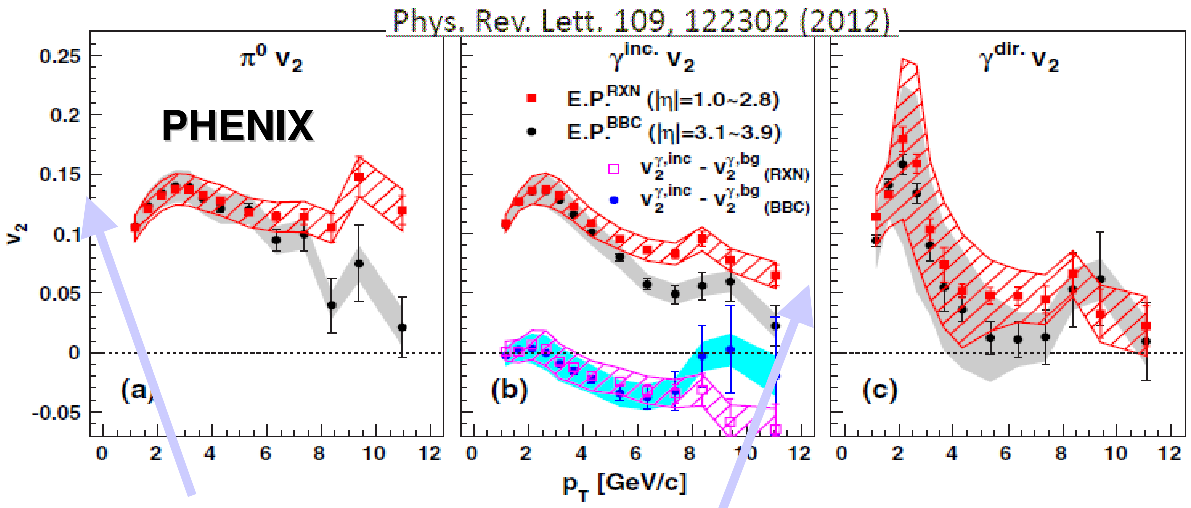


❑ Photon spectra show sensitivity to the dynamical evolution

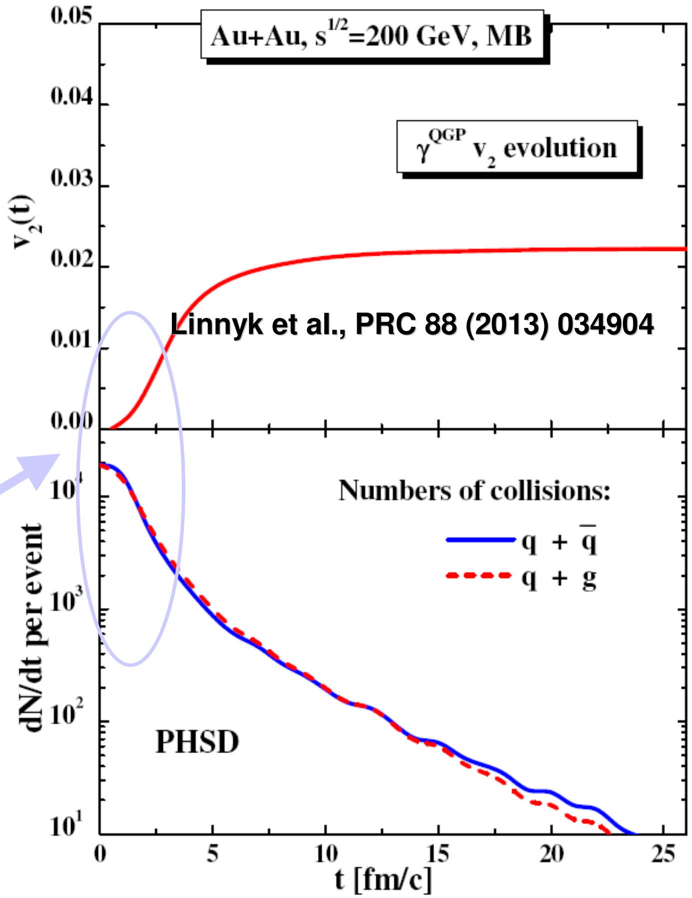
Lesson 1:

➔ in order to be conclusive on photon production, the models must reproduce the final hadronic spectra, i.e. to pass the basic check (Step 1) for the adequate dynamical description of the HIC!

PHENIX: Photon v_2 puzzle



$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos(n(\phi - \Psi_n^{RP}))\right)$$



- **PHENIX (also now ALICE):**
  strong elliptic flow of photons $v_2(\gamma^{dir}) \sim v_2(\pi)$
- **Result from a variety of models:** $v_2(\gamma^{dir}) << v_2(\pi)$

- **Problem:** QGP radiation occurs at early times when flow is not yet developed → expected $v_2(\gamma^{QGP}) \to 0$

v_2 = weighted average $v_2 = \frac{\sum_i N^i \cdot v_2^i}{\sum_i N^i}$ → a large QGP contribution gives small $v_2(\gamma^{QGP})$

- **NEW** (QM'2014): **PHENIX, ALICE experiments - large photon v_3 !**

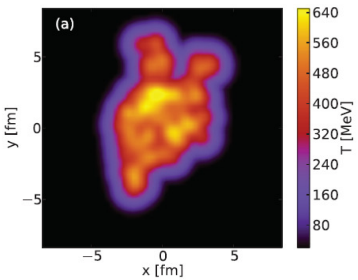
⇨ **Challenge for theory – to describe spectra, v_2, v_3 simultaneously !**

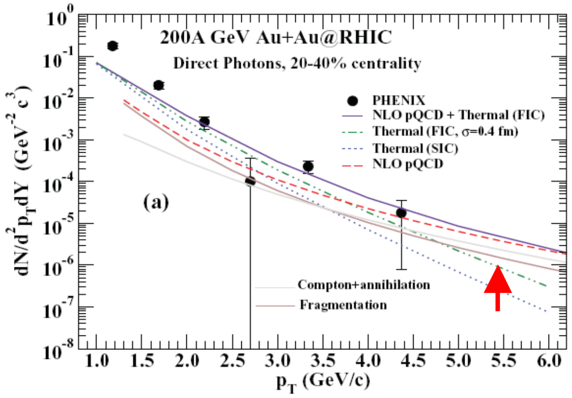
Photon production in hydrodynamical models

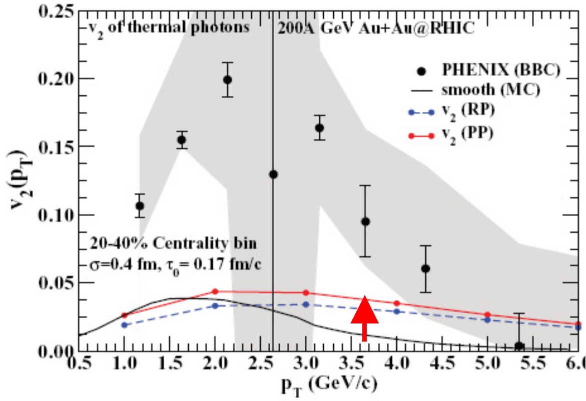
❑ **Step 2: ➔ From smooth Glauber initial conditions to event-by-event hydro with fluctuating initial conditions**

Jyväskylä ideal hydro

R. Chatterjee et al., PRC 88, 034901 (2013)





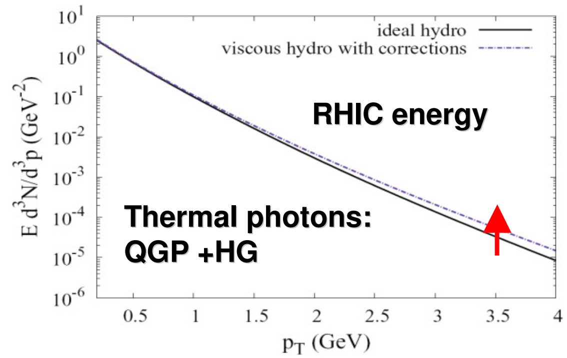


➔ Lesson 2: effect of fluctuating initial conditions:
slight increase at high p_T for yield and v_2 ➔ **small effect, but right direction!**

❑ **Step 3: ➔ From ideal to viscous hydro**

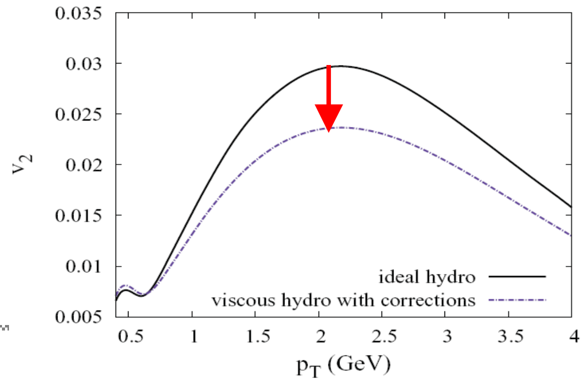
(3+1)D MUSIC (McGill)
M. Dion et al., PRC84 (2011) 064901

(2+1)D VISH2+1 (Ohio State) :
C. Shen et al., arXiv:1308.2111, arXiv:1403.7558



➔ Lesson 3: effect of shear viscosity:

* small enhancement of the photon yield
* suppression of photon v_2
* effect on v_2 for photons is stronger than for hadrons



Step 4: Hydro with pre-equilibrium flow

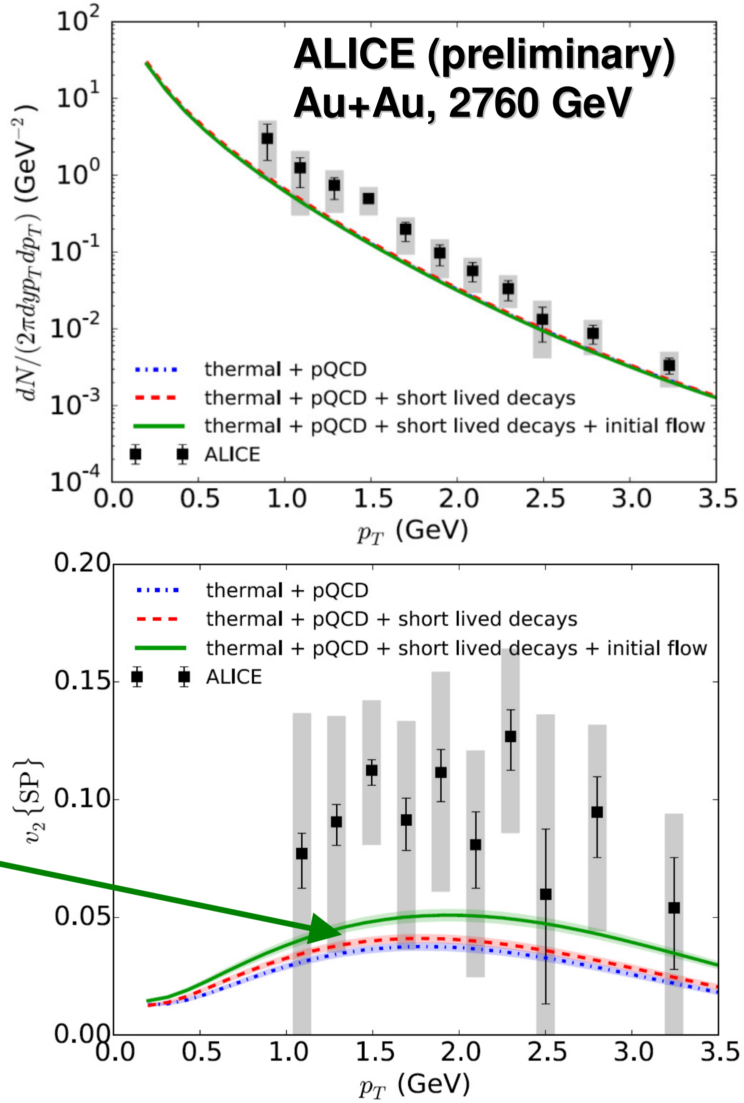
- ❑ ‚Initial' flow: rapid increase in bulk v_2 in fireball model
  van Hees, Gale, Rapp, PRC84 (2011) 054906

- ❑ pre-equilibrium flow in (2+1)D VISH2+1 - 2014:
  C. Shen et al., arXiv:1308.2111, arXiv:1403.7558; 1407.8583

- viscous QGP and HG fluid (η/s=0.18)
- Initial: ‚bumpy' e-b-e from MC Glauber /KLN
- EoS: lQCD
- QGP photon rate: AMY
- HG photon rate: TGR for meson gas with viscous corrections

• Generation of pre-equilibrium flow:
using free-streaming model to evolve the partons right after the collisions to 0.6 fm/c
+ Landau matching to switch to viscous hydro

➔ quick development of momentum anisotropy with saturation near T_C



➔ Lesson 4: Pre-equilibrium flow:
- small effect on photon spectra
- slight increase of v_2

Warning: results can be considered as upper limit for the pre-equilibrium flow effect!

What else?!

- Further **improvements of hydro models** ?

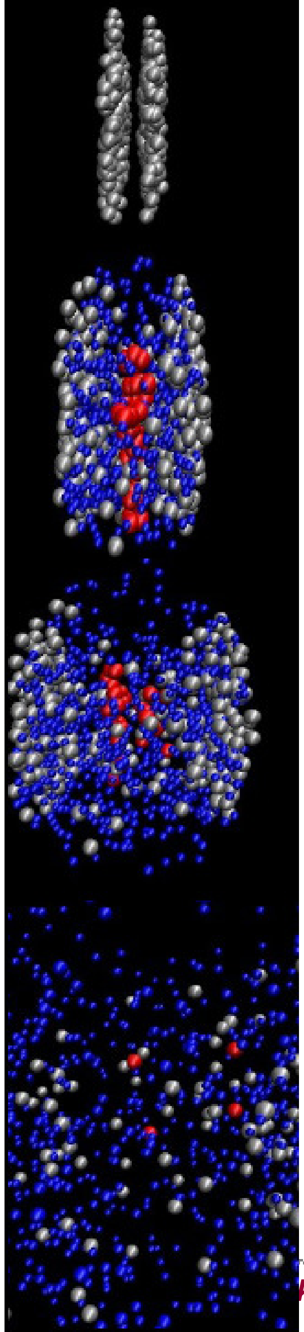
  - Bulk viscosity
  - Modeling of initial pre-equlibrium effects
  - …

- **Non-equilibrium dynamics** ?
- Missing strength related to **hadronic stage in hydro** ?

⇒ From hydro to non-equilibrium **microscopic transport models** :

use **PHSD as a ‚laboratory‘** for that

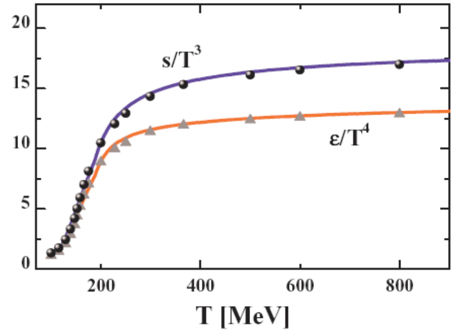
Parton-Hadron-String-Dynamics (PHSD)



PHSD is a non-equilibrium transport model which provides the microscopic description of the full collision evolution

Basic ideas:

- explicit phase transition from hadrons to partons
- lQCD EoS (cross over) for the partonic phase
- explicit parton-parton interactions - between quarks and gluons
- dynamical hadronization
- off-shell hadronic collision dynamics in the final reaction phase

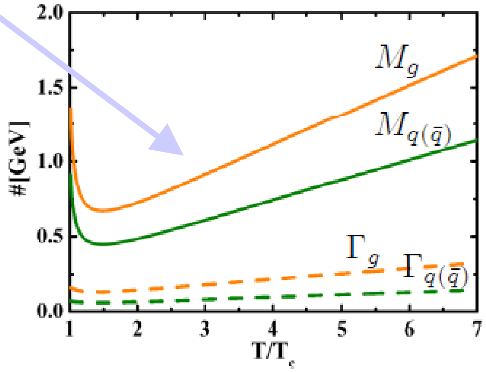


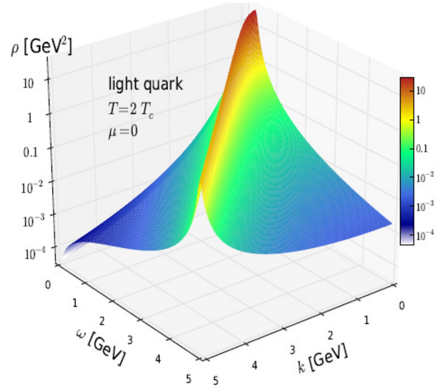
QGP phase is described by the Dynamical QuasiParticle Model (DQPM)

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)

- strongly interacting quasi-particles
- massive quarks and gluons (g, q, q_{bar}) with sizeable collisional widths in self-generated mean-field potential
- Spectral functions:

$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \quad (i = q, \bar{q}, g)$$





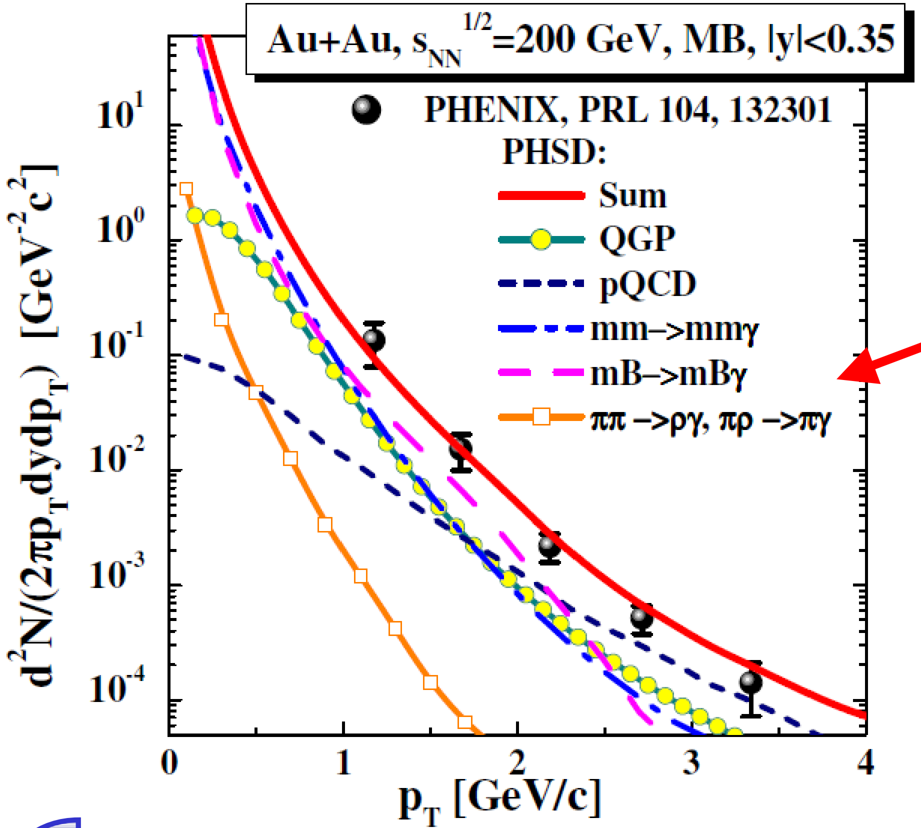
DQPM matches well lattice QCD

Transport theory: generalized off-shell transport equations based on 1st order gradient expansion of Kadanoff-Baym equations (applicable for strongly interacting systems!)

W. Cassing, E. B., PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

PHSD: photon spectra at RHIC: QGP vs. HG ?

- **Direct photon spectrum (min. bias)**



The slope parameter T_{eff} (in MeV)			
PHSD			PHENIX
QGP	hadrons	Total	[38]
260 ± 20	200 ± 20	220 ± 20	233 ± 14 ± 19

Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908

PHSD:

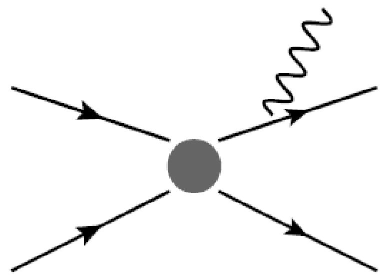
- **QGP gives up to ~50% of direct photon yield below 2 GeV/c**

! sizeable contribution of hadronic sources, dominant – meson-meson (mm) and meson-Baryon (mB) bremsstrahlung

$$m+m \rightarrow m+m+\gamma,$$

$$m+B \rightarrow m+B+\gamma,$$

$$m=\pi,\eta,\rho,\omega,K,K^*,\ldots$$
$$B=p$$



!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !

Measured Teff > ‚true' T ➔ ‚blue shift' due to the radial flow!

Cf. Hydro: Shen et al., PRC89 (2014) 044910

Bremsstrahlung – theoretical uncertainties

❑ **Uncertainties in the Bremsstrahlung channels in the previous PHSD results :**

1) based on the Soft-Photon-Approximation (SPA) (factorization = strong x EM)

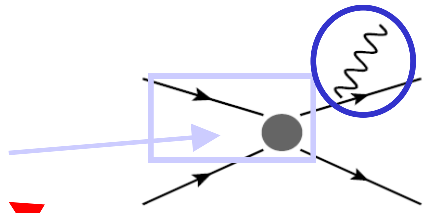
❑ **Soft Photon Approximation (SPA):**

$m_1+m_2 \rightarrow m_1+m_2+\gamma$

C. Gale, J. Kapusta, Phys. Rev. C 35 (1987) 2107

$$q_0 \frac{d^3\sigma^\gamma}{d^3q} = \frac{\alpha}{4\pi}\frac{\bar{\sigma}(s)}{q_0^2}$$

$$\bar{\sigma}(s) = \frac{s-(M_1+M_2)^2}{2M_1^2}\sigma(s),$$

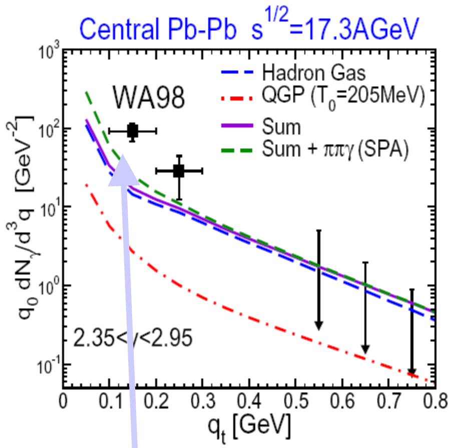


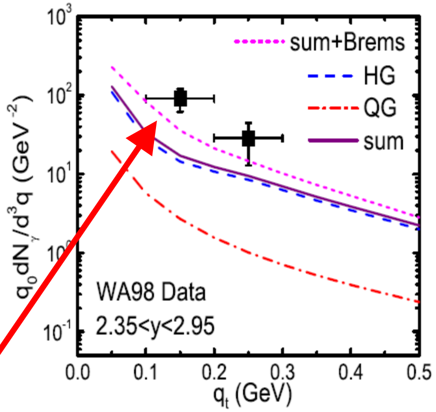
2) no experimental constraints on m+m and m+B differential elastic cross sections (used σ_{el}^{mm}=10mb)

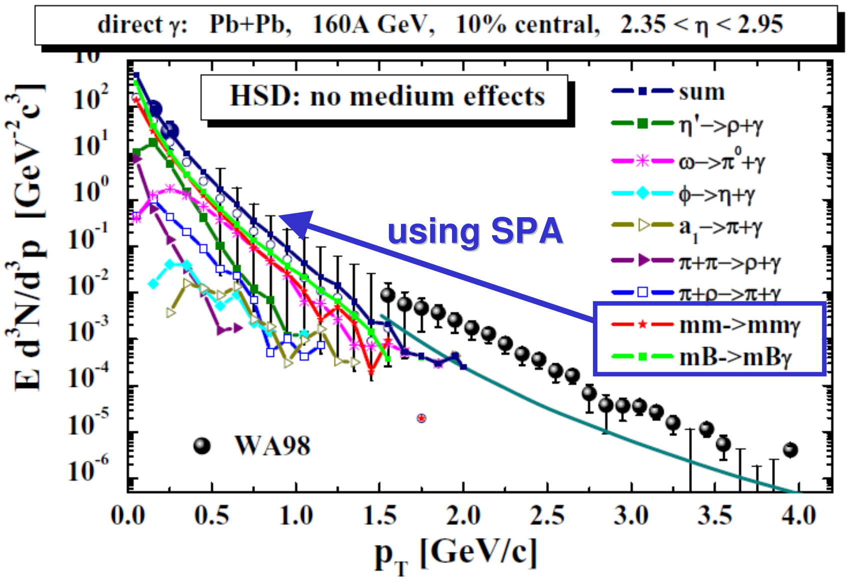
❑ **Bremsstrahlung: seen at SPS - WA98**

HSD: E. B., Kiselev, Sharkov, PR C78 (2008) 034905

Firebal model: Liu, Rapp, Nucl. Phys. A 96 (2007) 101







▪ effective chiral model for $\pi\pi \rightarrow \pi\pi\gamma$, $\pi K \rightarrow \pi K\gamma$ bremsstrahlung gives larger contribution than SPA

➔ mm and mB Bremsstrahlung is an important source of soft photons at SPS energies!

Bremsstrahlung – theoretical uncertainties

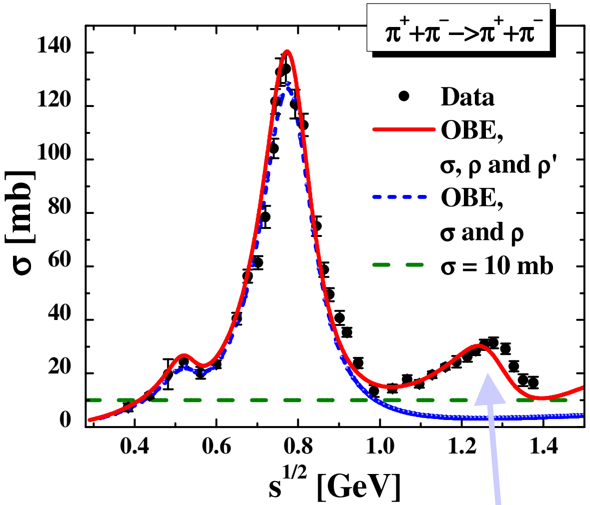
Beyond the Soft-Photon Approximation:

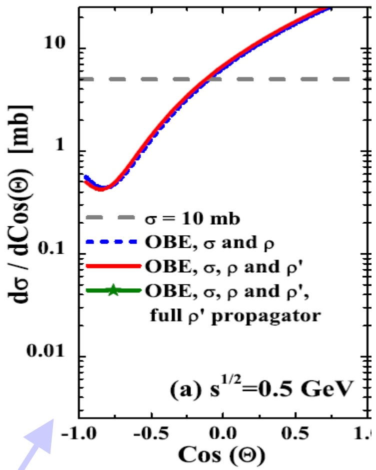
- **Effective chiral Lagrangian with σ, ρ, and ρ' exchange for π+π (chiral OBE model) :**

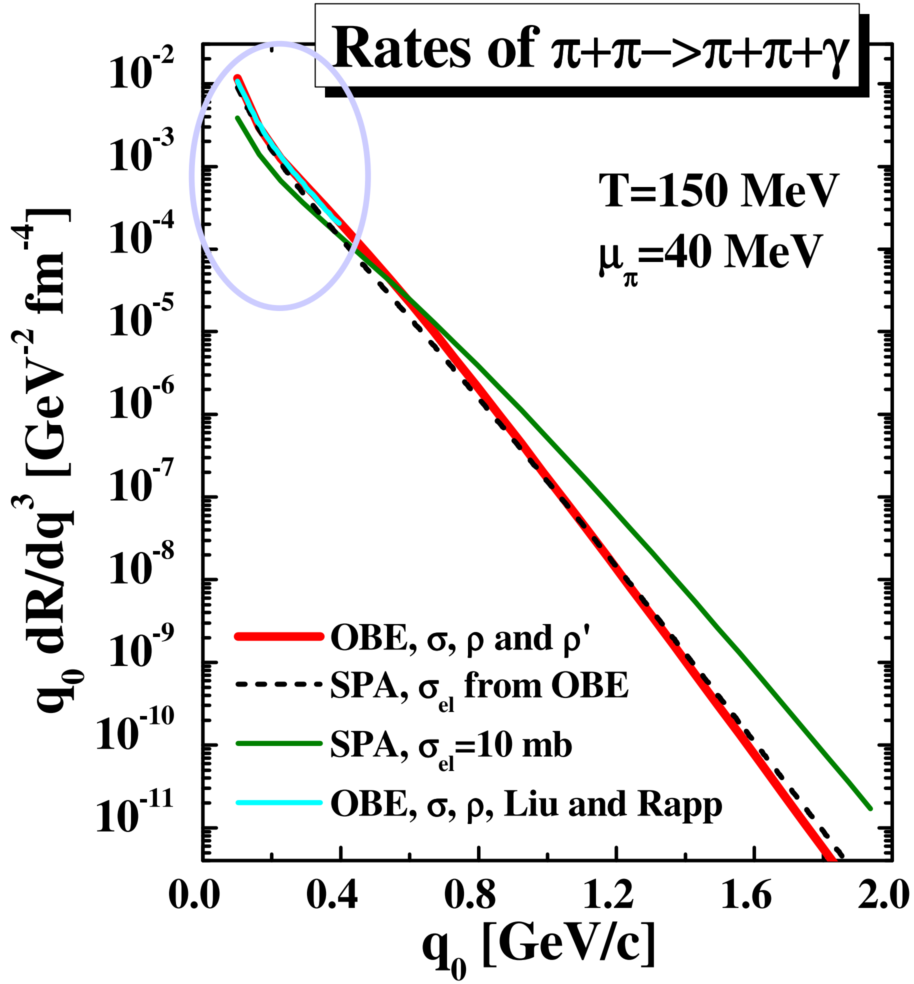
$$\mathcal{L} = g_\sigma\, \sigma \partial_\mu \pi \cdot \partial^\mu \pi + g_\rho\, \rho^\mu \cdot \pi \times \partial_\mu \pi + g_f\, f_{\mu\nu} \partial^\mu \pi \cdot \partial^\nu \pi$$

elastic π+π cross sections from OBE:

total **differential**







- Tensor meson ρ' important at higher sqrt(s) and $p_T(\gamma)$
- Strong angular dependence of elastic cross section

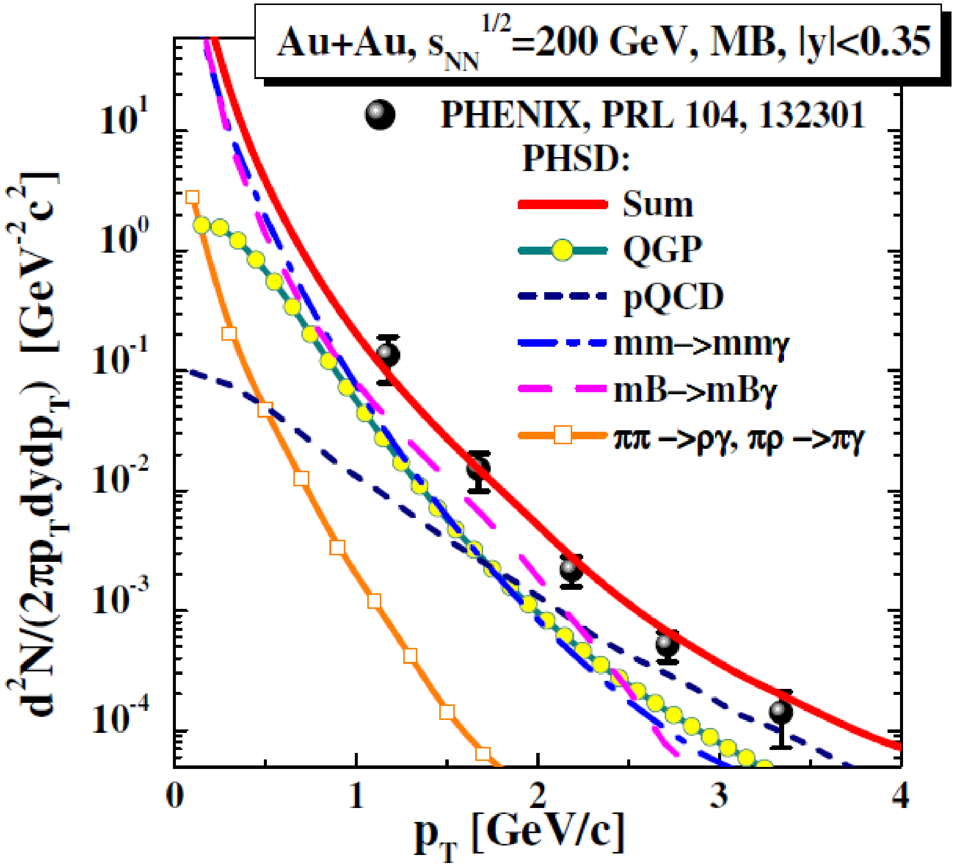
Linnyk et al., in preparation

PHSD: new photon spectra at RHIC beyond SPA

- **Direct photon spectrum (min. bias)**

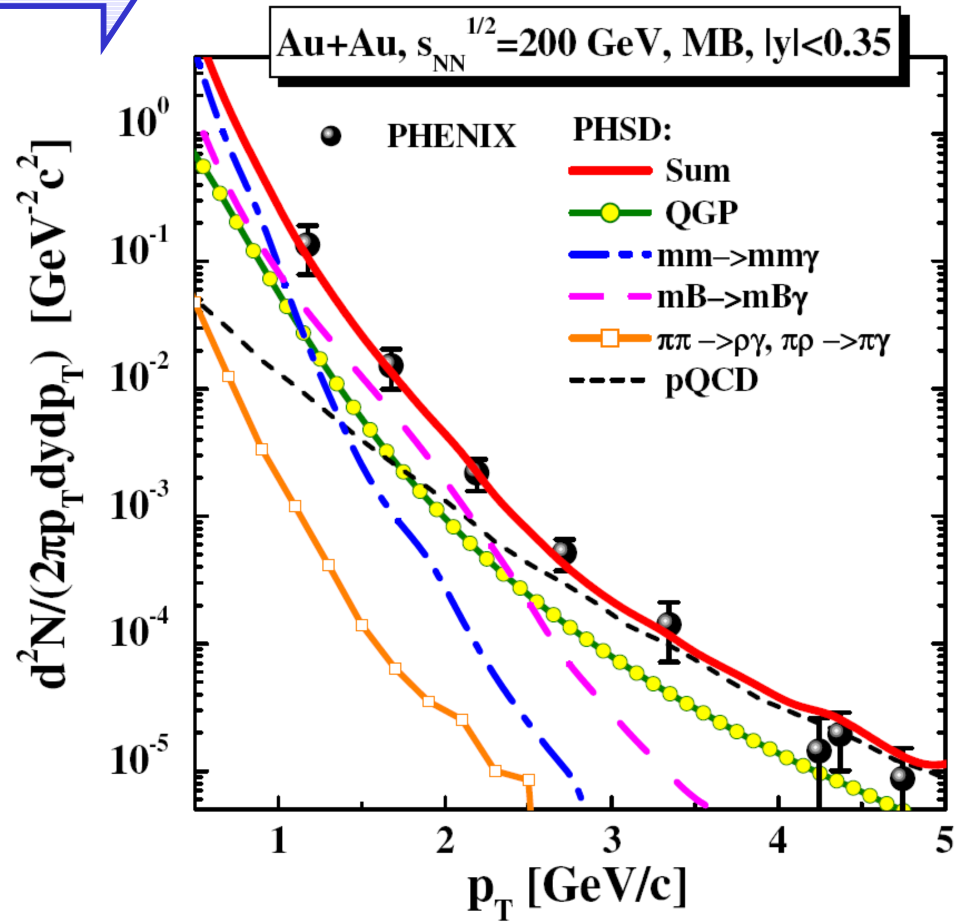
❑ **m+m bremsstrahlung** based on the **Soft-Photon-Approximation (SPA)**

Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



❑ **m+m bremsstrahlung** based on the **chiral OBE model**

Linnyk et al., in preparation



❑ enhancement of low p_T yield

❑ reduction of high p_T yield from m+m bremsstrahlung

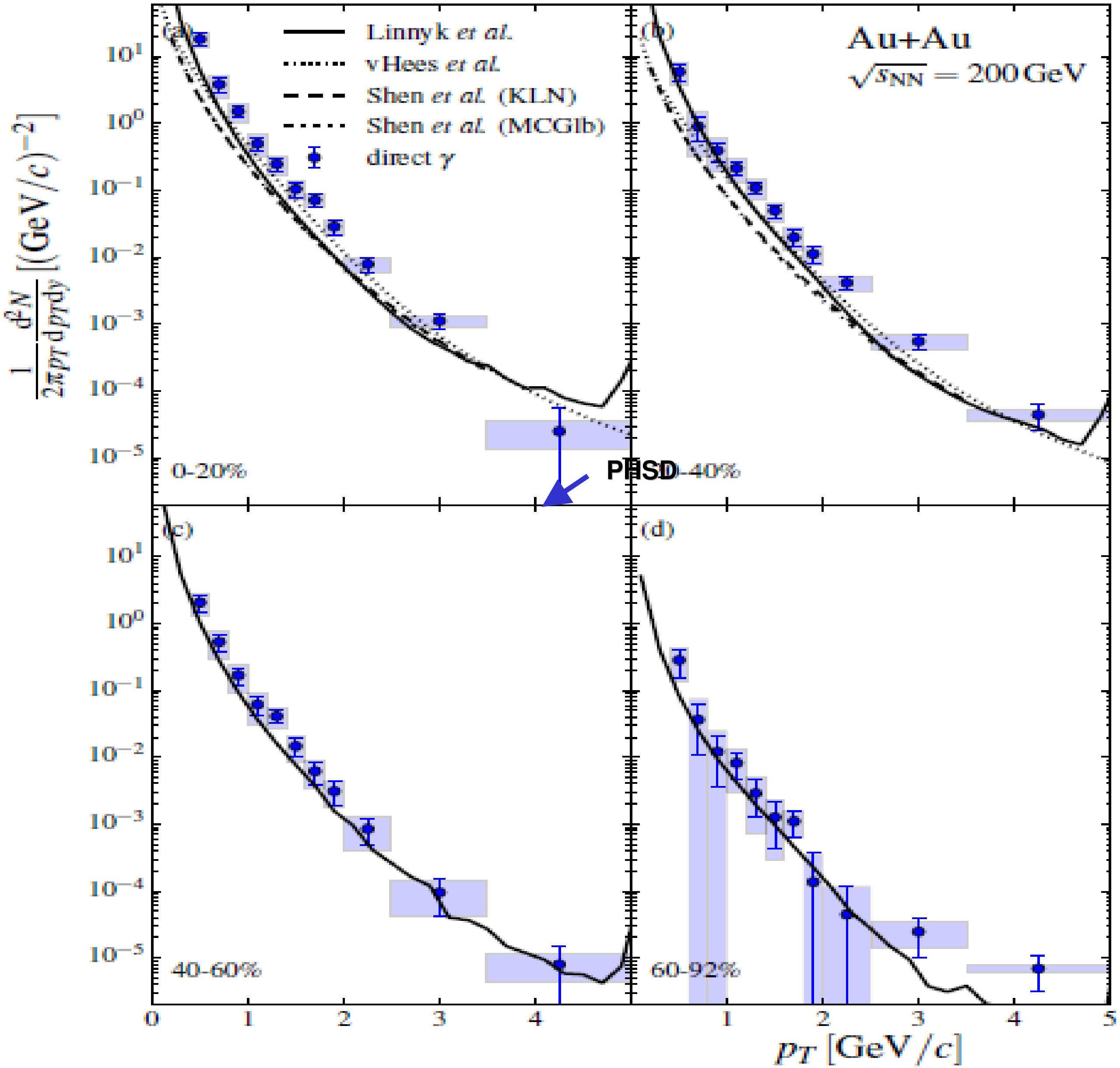
➔ m+m (and m+B) bremsstrahlung dominates photon spectra at low p_T

Photon p_T spectra at RHIC for different centralities

from talk by S. Mizuno at QM'2014

PHENIX data - arXiv:1405.3940

PHSD predictions:
O. Linnyk et al, Phys. Rev. C 89 (2014) 034908



❑ How to separate hadronic and partonic contributions ?

➔ Look at the centrality dependence of photon yield!

❑ PHSD approximately reproduces the centrality dependence of photon spectra

❑ mm and mB bremsstrahlung is dominant in peripheral collisions in the PHSD calculations

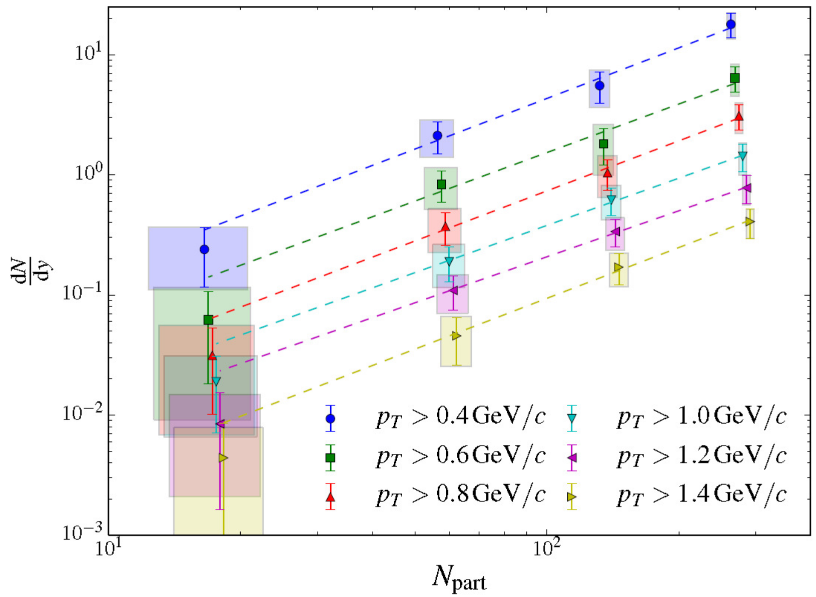
Centrality dependence of the ‚thermal' photon yield

O. Linnyk et al, Phys. Rev. C 89 (2014) 034908

PHENIX (arXiv:1405.3940):

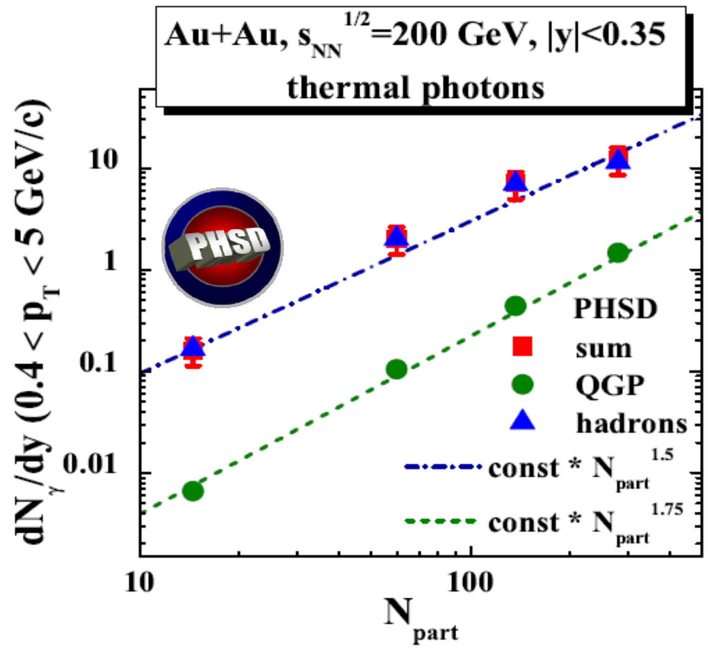
scaling of thermal photon yield vs centrality:
$dN/dy \sim N_{part}^{\alpha}$ with $\alpha \sim 1.48 \pm 0.08$

('Thermal' photon yield = direct photons - pQCD)



PHSD predictions:

- Hadronic channels scale as ~ $N_{part}^{1.5}$
- Partonic channels scale as ~$N_{part}^{1.75}$



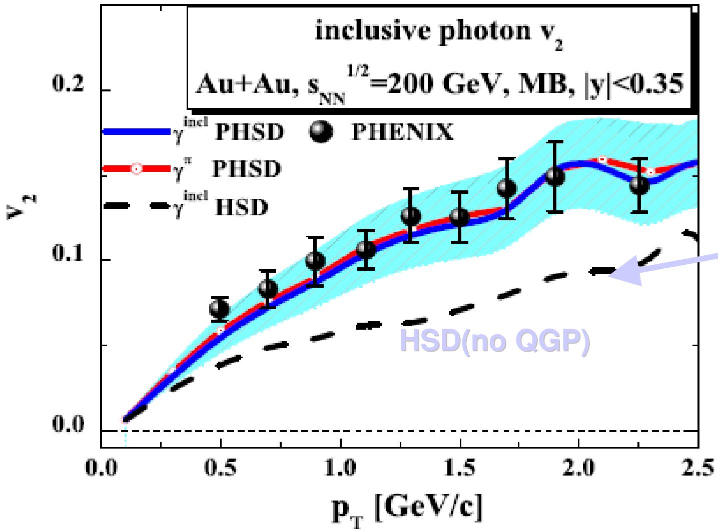
- **PHSD:** scaling of the thermal photon yield with N_{part}^{α} with $\alpha \sim 1.5$
- similar results from viscous hydro:
  (2+1)d VISH2+1: α(HG) ~1.46, α(QGP) ~2, α(total) ~1.7

➔ **What do we learn?**
Indications for a dominant hadronic origin of thermal photon production?!

Are the direct photons a barometer of the QGP?

❑ Do we see the **QGP pressure** in $v_2(\gamma)$ if the photon productions is **dominated by hadronic sources?**

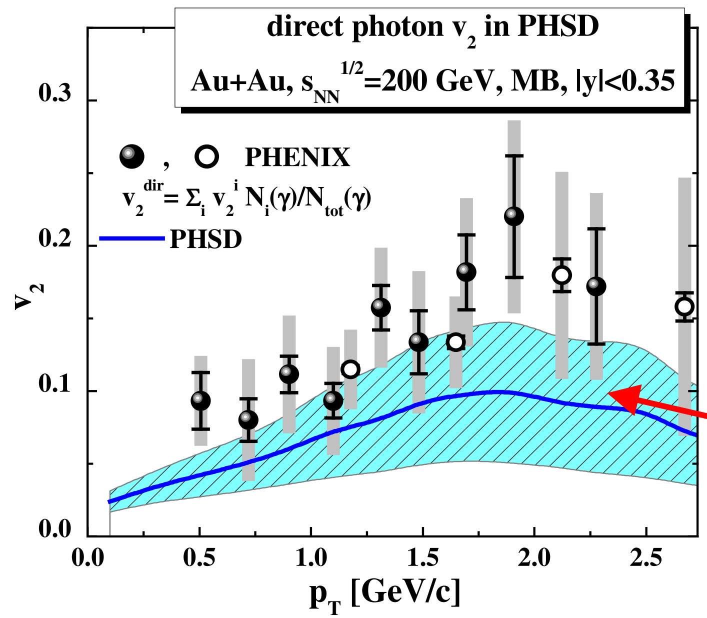
PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



1) $v_2(\gamma^{incl}) = v_2(\pi^0)$ - **inclusive photons** dominanty stem from π^0 decays

- HSD (without QGP) underestimates v_2 of hadrons and inclusive photons by a factor of 2, wheras the PHSD model with QGP is consistent with exp. data

➔ The **QGP causes the strong elliptic flow of photons indirectly,** by enhancing the v_2 of final hadrons due to the partonic interactions



Direct photons (inclusive(=total) – decay):

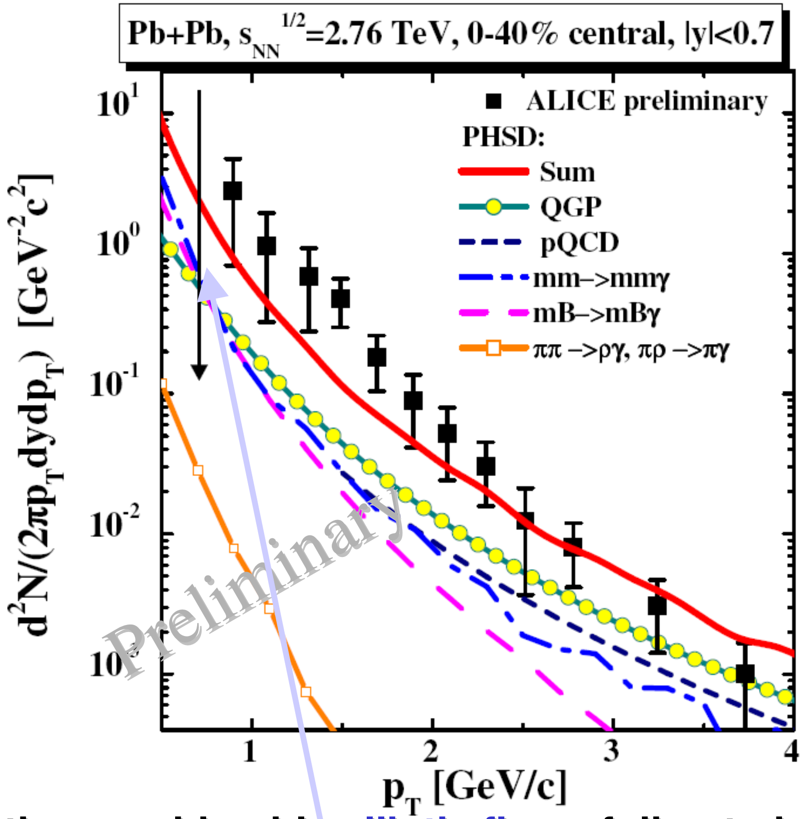
2) $v_2(\gamma^{dir})$ of **direct photons** in PHSD underestimates the PHENIX data :

$v_2(\gamma^{QGP})$ **is very small**, but QGP contribution is up to 50% of total yield ➔ lowering flow

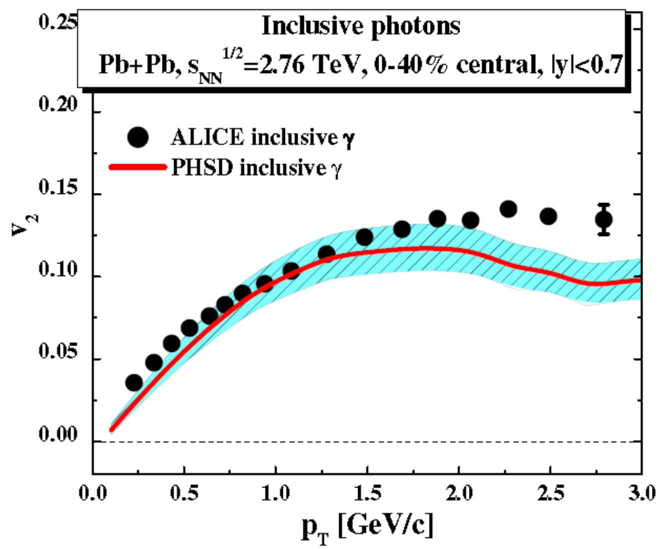
➔**PHSD:** $v_2(\gamma^{dir})$ comes from **mm and mB bremsstrahlung !**

Photons from PHSD at LHC

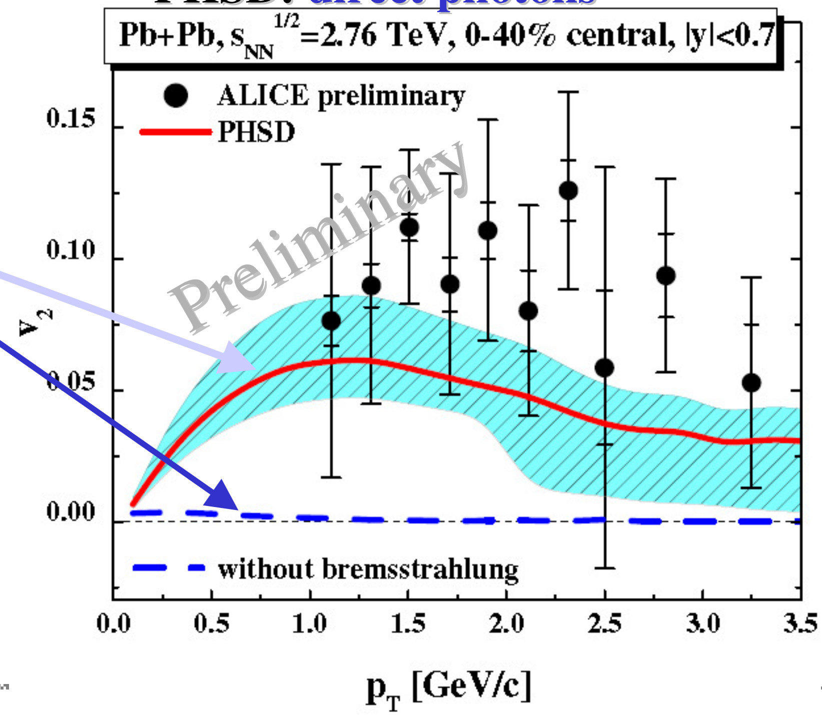
PHSD- preliminary: Olena Linnyk



PHSD: v_2 of inclusive photons



PHSD: direct photons



- Is the considerable elliptic flow of direct photons at the LHC also of hadronic origin as for RHIC?!
- The photon elliptic flow at LHC is lower than at RHIC due to a larger relative QGP contribution / longer QGP phase.

➔ LHC (similar to RHIC):
hadronic photons dominate spectra and v_2

Towards the solution of the v_2 puzzle

- Is hadronic bremsstrahlung a ‚solution'?

Other scenarios:

- Early-time magnetic field effects ?

Basar, Kharzeev, Skokov, PRL109 (2012) 202303; Basar, Kharzeev, Shuryak, PRC 90 (2014) 014905
„ … a novel photon production mechanism from the conformal anomaly of QCD-QED and the existence of strong (electro)-magnetic fields in heavy- ion collisions."
Exp. checks: v_3 , centrality dependence of photon yield (PHENIX: arXiv:1405.3940)

- Glasma effects ?

L. McLerran, B. Schenke, arXiv: 1403.7462

„ … Photon distributions from the Glasma are steeper than those computed in the Thermalized Quark Gluon Plasma (TQGP). Both the delayed equilibration of the Glasma and a possible anisotropy in the pressure lead to a slower expansion and mean times of photon emission of fixed energy are increased."

- Pseudo-Critical Enhancement of thermal photons near T_C ?

H. van Hees, M. He, R. Rapp, NPA 933 (2014) 256

- non-perturbative effects - semi-QGP

Y. Hidaka, S. Lin, R. Pisarski et al., NPA931 (2014) 681

- ???

Messages from the photon study

- ❑ sizeable contribution from hadronic sources - at RHIC and LHC hadronic photons dominate spectra and v_2

- ❑ meson-meson (mm) and meson-Baryon (mB) bremsstrahlung are important sources of direct photons

- ❑ mm and mB bremsstrahlung channels can not be subtracted experimentally !

- ❑ The QGP causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of partons and final hadrons due to partonic interactions

Photons – one of the most sensitive probes for the dynamics of HIC!

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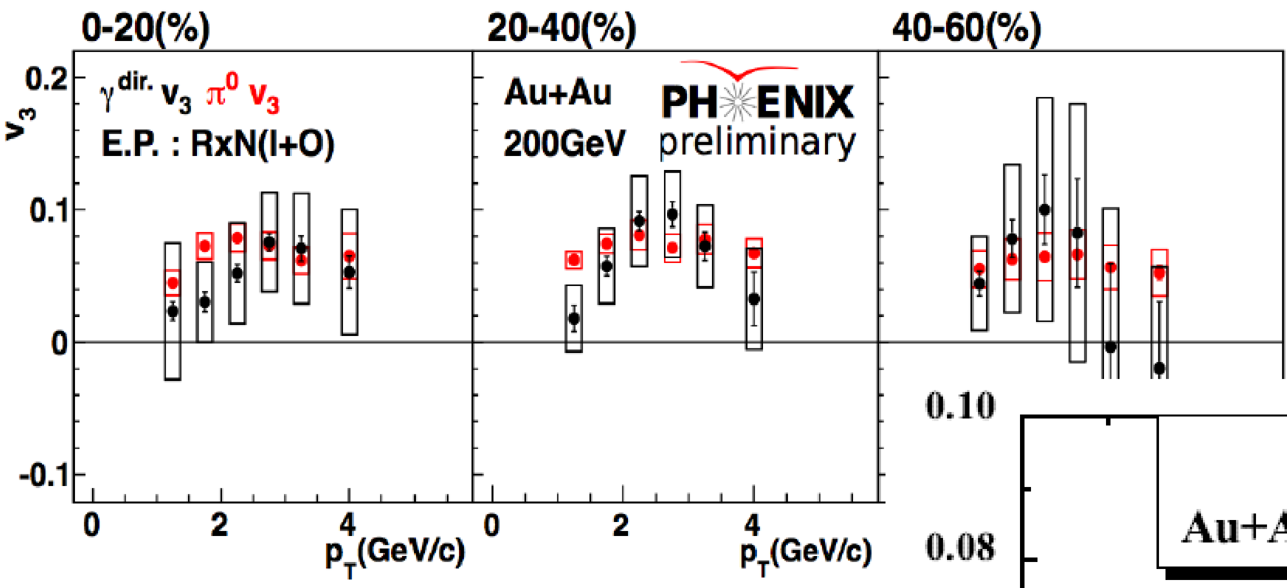
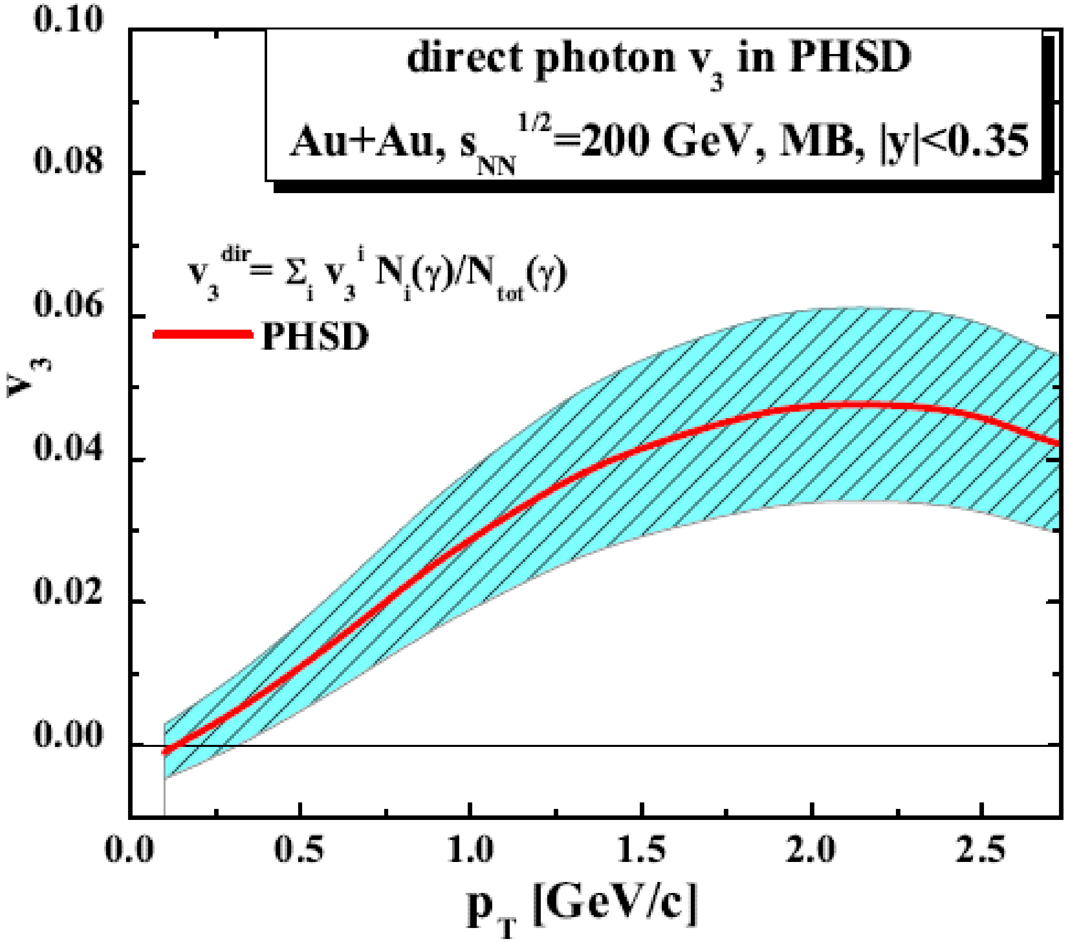
Thank you !

V_3 at RHIC



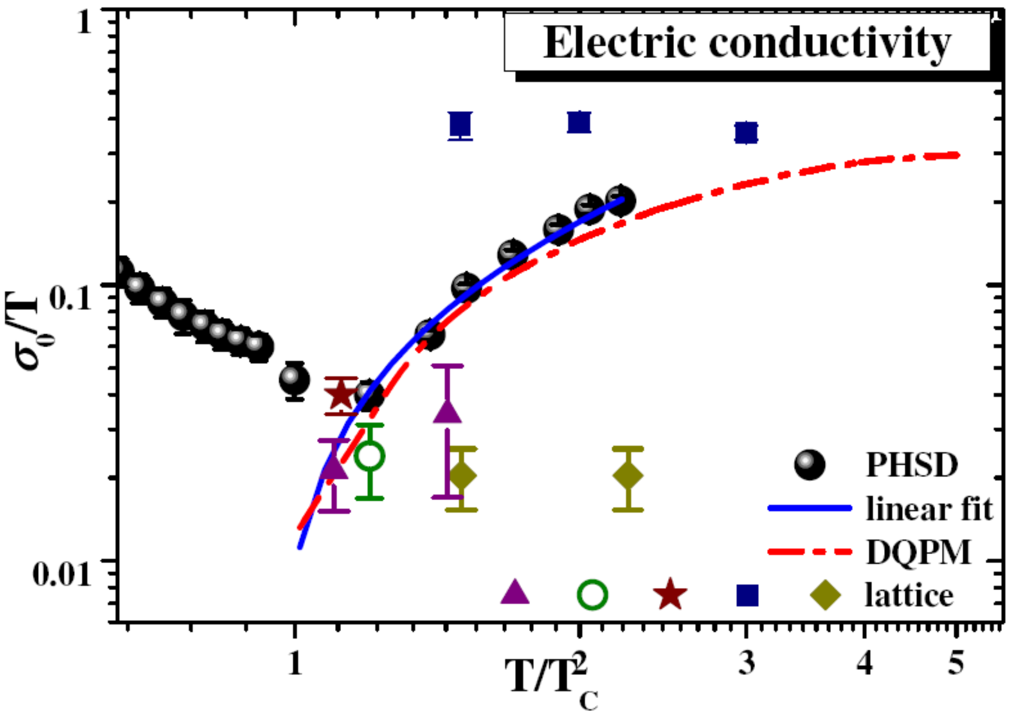
0-20(%)
20-40(%)
40-60(%)
$\gamma^{dir.}$ v_3 π^0 v_3
E.P. : RxN(I+O)
Au+Au
200GeV
PHENIX
preliminary
v_3
p_T(GeV/c)



direct photon v_3 in PHSD
Au+Au, $s_{NN}^{1/2}$=200 GeV, MB, |y|<0.35
$v_3^{dir} = \Sigma_i v_3^i N_i(\gamma)/N_{tot}(\gamma)$
PHSD
v_3
p_T [GeV/c]

Properties of parton-hadron matter: electric conductivity

- The response of the strongly-interacting system in equilibrium to an **external electric field eE_z** defines the **electric conductivity σ_0**:



$$\frac{\sigma_0}{T} = \frac{j_{eq}}{E_z T},$$

$$j_z(t) = \frac{1}{V}\sum_j eq_j \frac{p_z^j(t)}{M_j(t)},$$

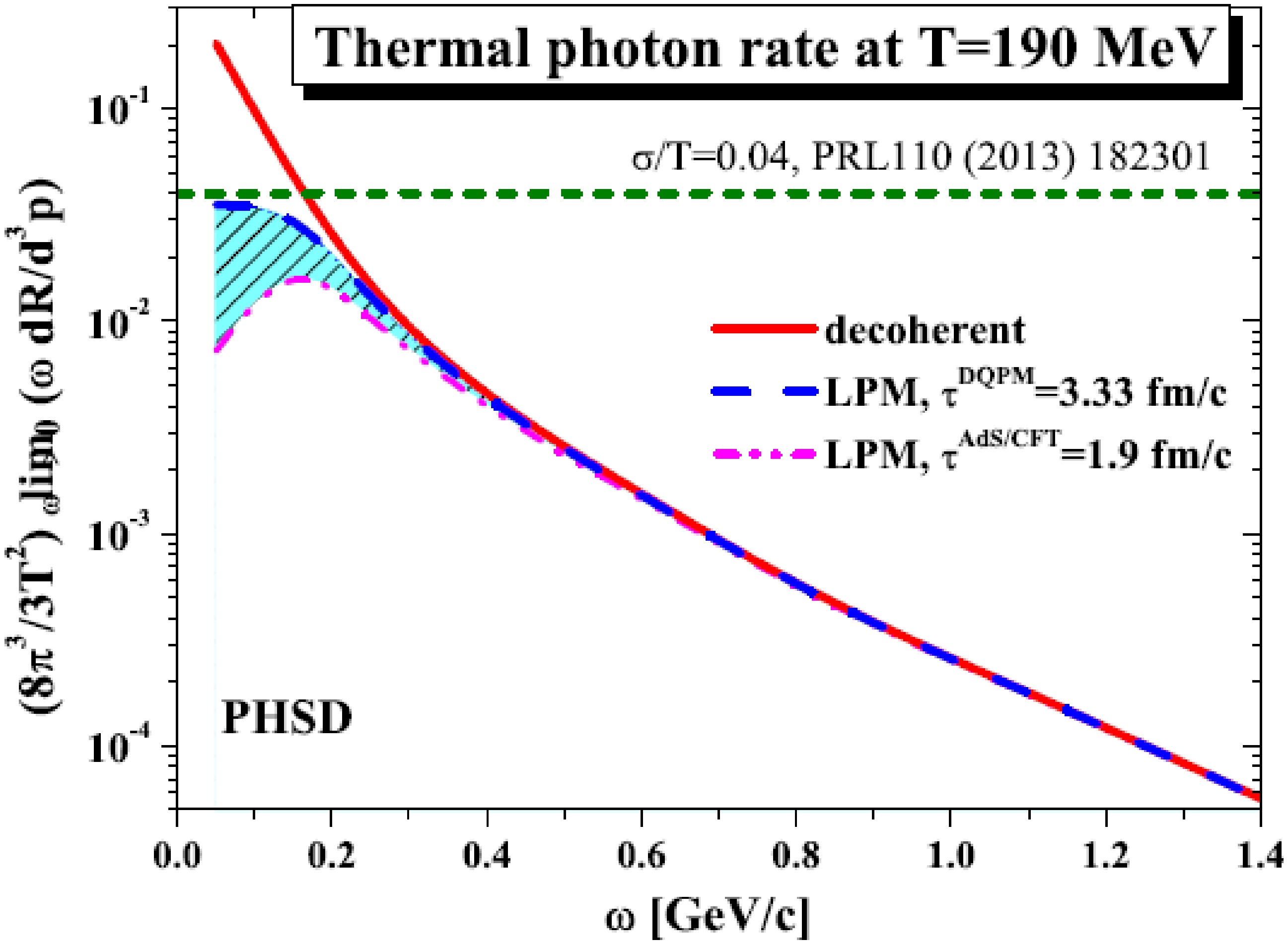
➔the **QCD matter** even at $T \sim T_c$ is a **much better electric conductor than Cu or Ag** (at room temperature) by a factor of 500 !

❑ **Photon (dilepton) rates** at $q_0 \to 0$ are related to electric conductivity σ_0
➔ Probe of **electric properties of the QGP**

$$q_0 \frac{dR}{d^4x\, d^3q}\bigg|_{q_0 \to 0} = \frac{T}{4\pi^3}\sigma_0$$

W. Cassing et al., PRL 110(2013)182301

LPM effect

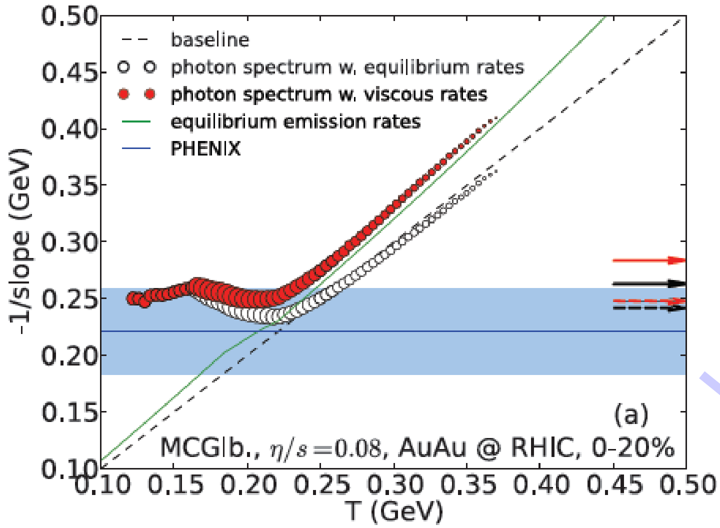

Thermal photon rate at T=190 MeV
σ/T=0.04, PRL110 (2013) 182301
decoherent
LPM, τ^DQPM=3.33 fm/c
LPM, τ^AdS/CFT=1.9 fm/c
PHSD
10^-1
10^-2
10^-3
10^-4
(8π³/3T²) lim (ω dR/d³p)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
ω [GeV/c]

Are thermal photons a QGP thermometer?

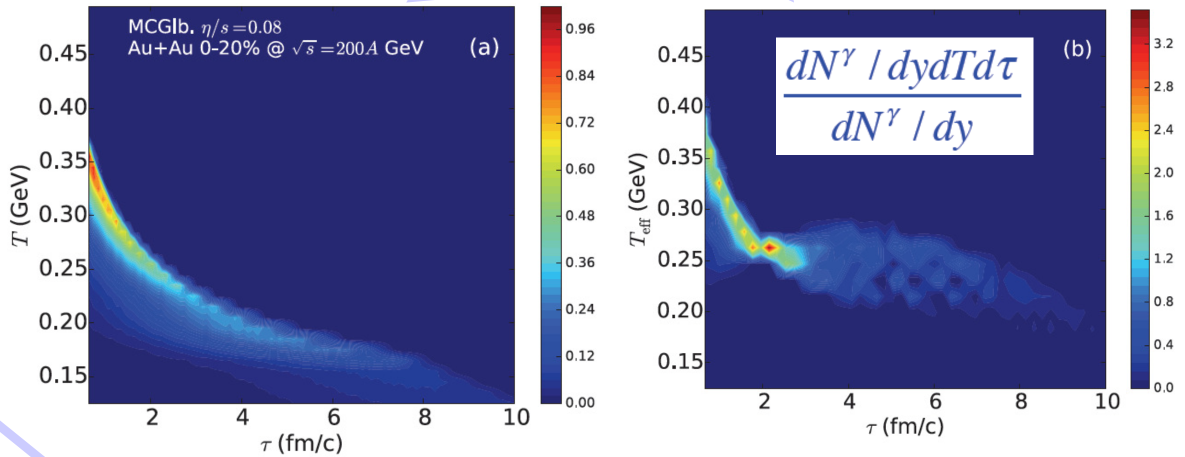
❑ (2+1)d viscous hydro VISH2+1 (Ohio)

C. Shen et al., PRC89 (2014) 044910; arXiv:1308.2440

- Time evolution of the effective temperature
- T_{eff}= -1/slope vs. local fluid cell temperature T



- Contour plots of differential photon yield vs. time and temperature T and T_{eff} :



Range of photon emission	Fraction of total photon yield	
	AuAu@RHIC 0–20% centr.	PbPb@LHC 0–40% centr.
T = 120–165 MeV	17%	15%
T = 165–250 MeV	62%	53%
T > 250 MeV	21%	32%
τ = 0.6–2.0 fm/c	28.5%	26%
τ > 2.0 fm/c	71.5%	74%

Exp. Data:

- RHIC: T_{eff}=221+19+19 MeV
- LHC: T_{eff}=304+51 MeV

❑ Measured Teff > ‚true' T $\quad T_{eff} = \sqrt{\frac{1+v}{1-v}}\,T$

❑ ‚blue shift' due to the radial flow!

❑ only ~1/3 at LHC and ~1/4 at RHIC of total photons come from hot QCD (T>250 MeV)

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

DQPM describes QCD properties in terms of ‚resummed' single-particle Green's functions – in the sense of a two-particle irreducible (2PI) approach:

Gluon propagator: $\Delta^{-1} = P^2 - \Pi$ gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$

Quark propagator: $S_q^{-1} = P^2 - \Sigma_q$ quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

- the resummed properties are specified by complex self-energies which depend on temperature:
  - -- the real part of self-energies (Σ_q, Π) describes a dynamically generated mass (M_q,M_g);
  - -- the imaginary part describes the interaction width of partons (Γ_q, Γ_g)
- space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the potential energy density and the mean-field potential (1PI) for quarks and gluons (U_q, U_g)
- 2PI framework guaranties a consistent description of the system in- and out-off equilibrium on the basis of Kadanoff-Baym equations

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

Properties of interacting quasi-particles:
massive quarks and gluons (g, q, q_{bar})
with Lorentzian spectral functions :

$$A_i(\omega,T)=\frac{4\omega\Gamma_i(T)}{\left(\omega^2-\vec{p}^2-M_i^2(T)\right)^2+4\omega^2\Gamma_i^2(T)}$$

$$(i=q,\bar{q},g)$$

- **Modeling of the quark/gluon masses and widths → HTL limit at high T**
  - **quarks:**

    mass: $M^2_{q(\bar{q})}(T)=\frac{N_c^2-1}{8N_c}g^2\left(T^2+\frac{\mu_q^2}{\pi^2}\right)$

    width: $\Gamma_{q(\bar{q})}(T)=\frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$

  - **gluons:**

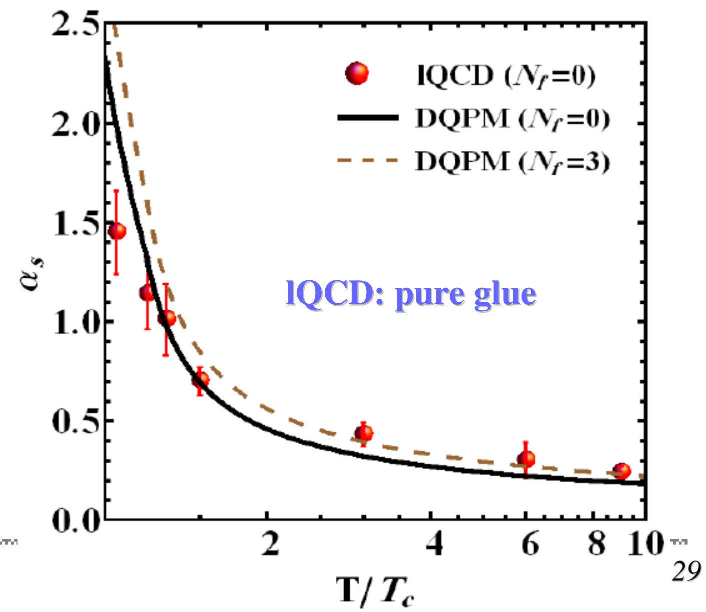
    $M_g^2(T)=\frac{g^2}{6}\left(\left(N_c+\frac{N_f}{2}\right)T^2+\frac{N_c}{2}\sum_q\frac{\mu_q^2}{\pi^2}\right)$

    $\Gamma_g(T)=\frac{1}{3}N_c\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$

$N_c = 3$, $N_f=3$

  - **running coupling (pure glue):**

$$\alpha_s(T)=\frac{g^2(T)}{4\pi}=\frac{12\pi}{(11N_c-2N_f)\ln[\lambda^2(T/T_c-T_s/T_c)^2]}$$

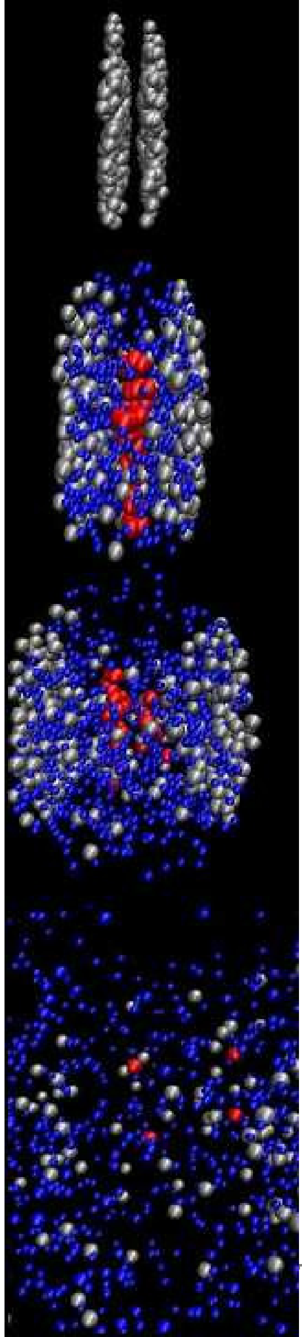


- **fit to lattice (lQCD) results (e.g. entropy density)**

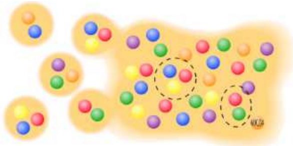
  with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
  (for pure glue N_f=0)

DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Parton Hadron String Dynamics

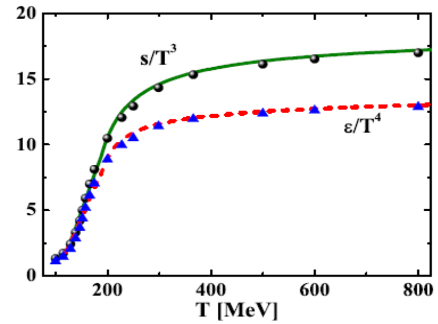


I. From hadrons to QGP:



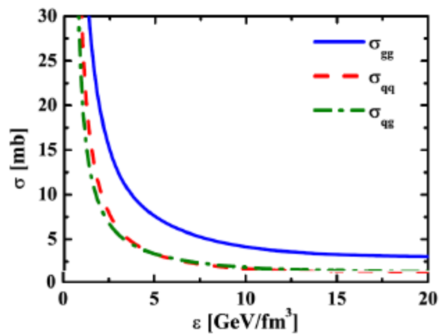
QGP phase:
$\varepsilon > \varepsilon_{critical}$

- Initial A+A collisions:
  - string formation in primary NN collisions
  - strings decay to pre-hadrons (*B* - baryons, *m* – mesons)
- Formation of QGP stage by dissolution of pre-hadrons into massive colored quarks + mean-field energy based on the Dynamical Quasi-Particle Model (DQPM) which defines quark spectral functions, masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$ + mean-field potential U_q at given ε – local energy density (related by lQCD EoS to *T* - temperature in the local cell)



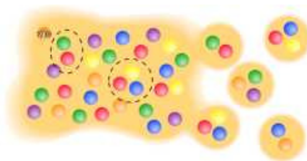
II. Partonic phase - QGP:

- quarks and gluons (= ‚dynamical quasiparticles') with off-shell spectral functions (width, mass) defined by the DQPM
- in self-generated mean-field potential for quarks and gluons U_q, U_g
- EoS of partonic phase: ‚crossover' from lattice QCD (fitted by DQPM)
- (quasi-) elastic and inelastic parton-parton interactions: using the effective cross sections from the DQPM



III. Hadronization: based on DQPM

- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings' (strings act as ‚doorway states' for hadrons)

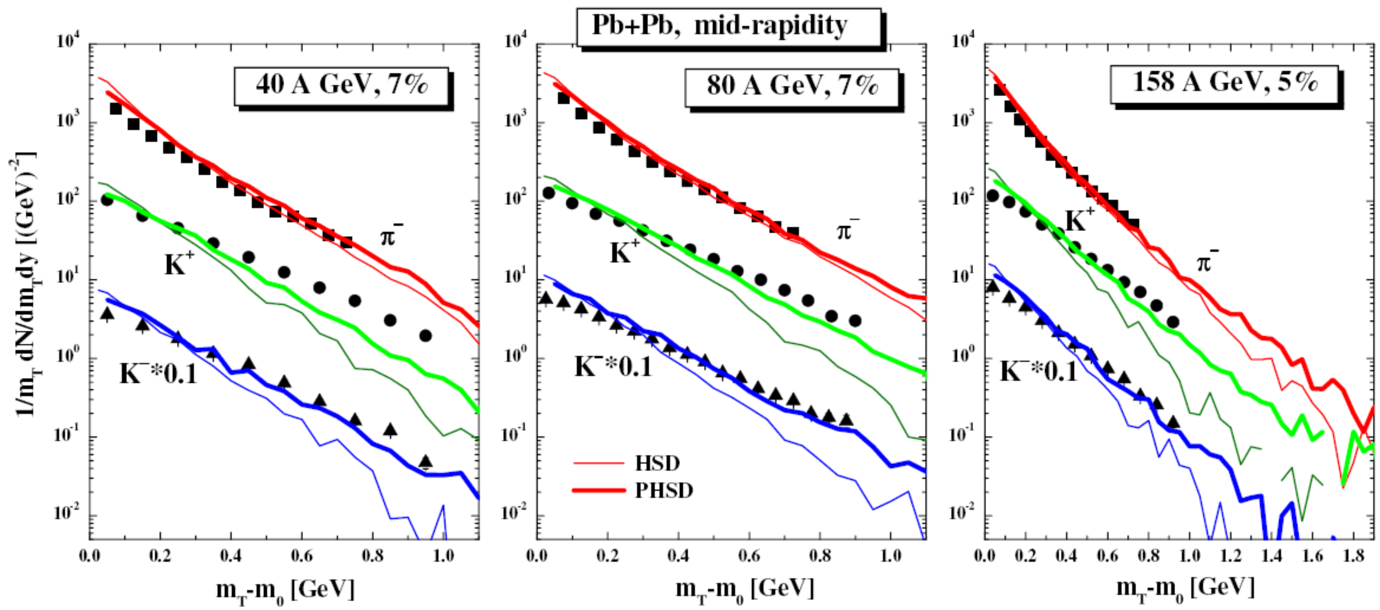


IV. Hadronic phase: hadron-string interactions – off-shell HSD

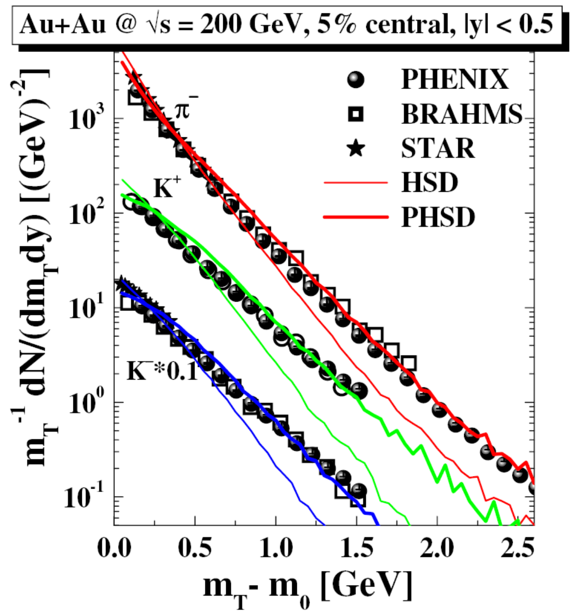
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

Transverse mass spectra from SPS to RHIC

Central Pb + Pb at SPS energies



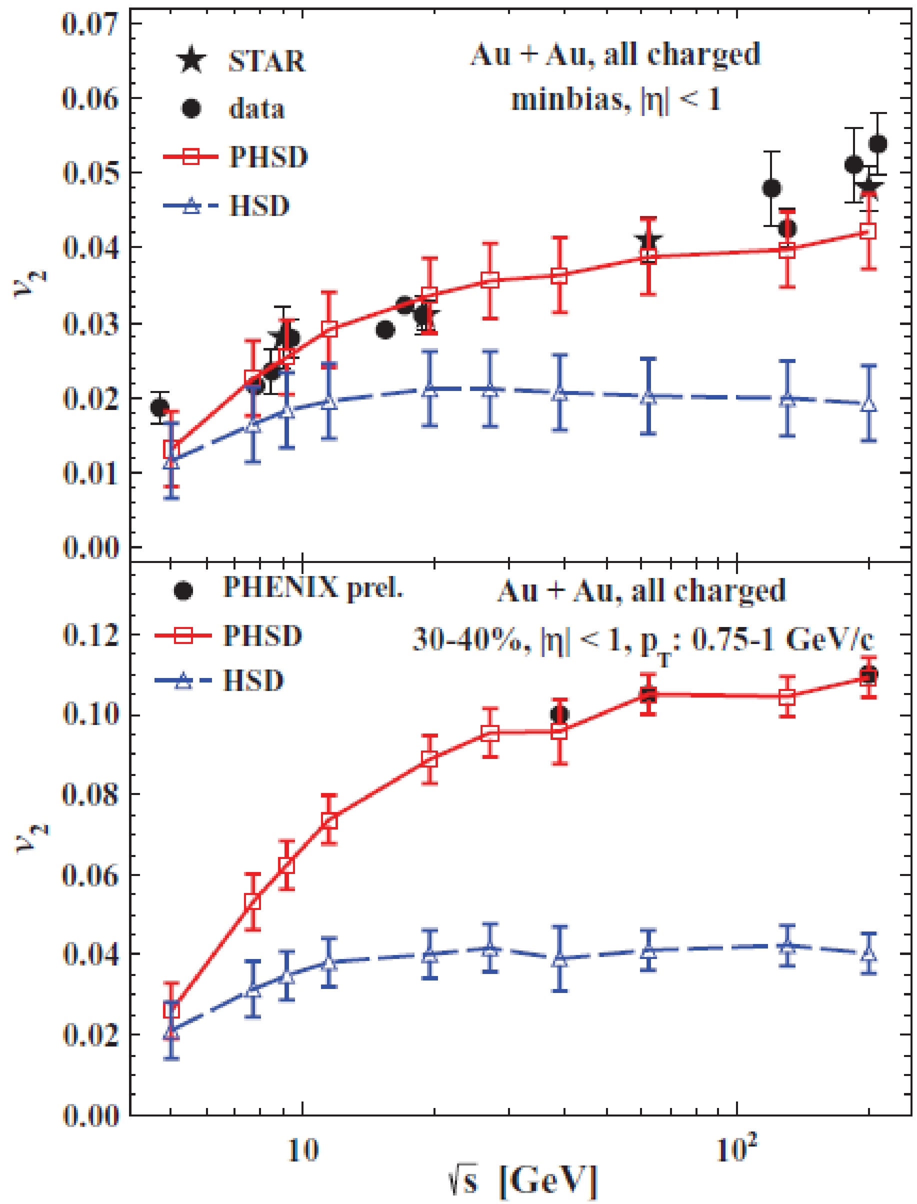
Central Au+Au at RHIC

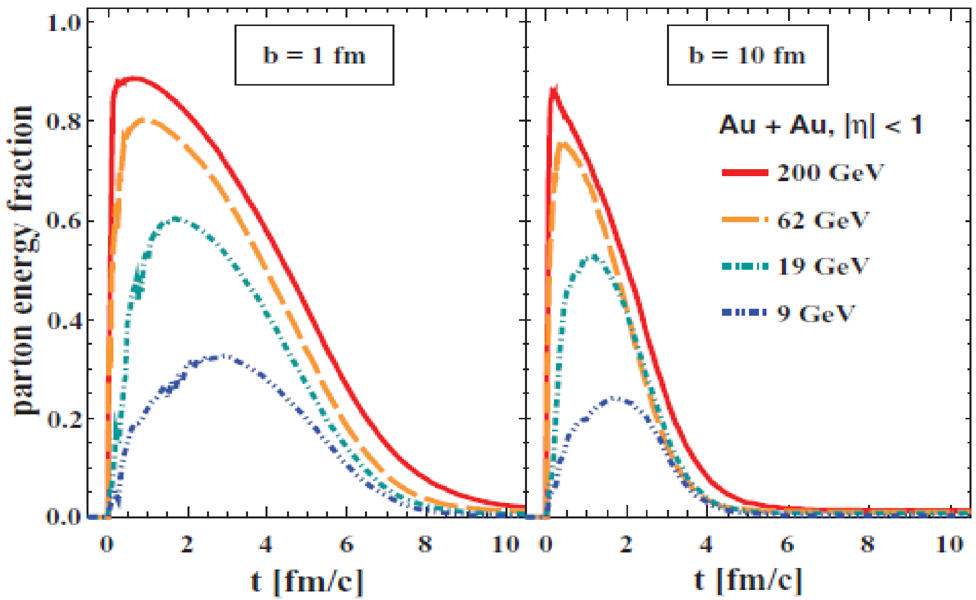


- **PHSD** gives **harder m_T spectra** and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at **low SPS** (and low FAIR, NICA) energies the **effect of the partonic phase decreases** due to the decrease of the partonic fraction

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

Elliptic flow v_2 vs. collision energy for Au+Au



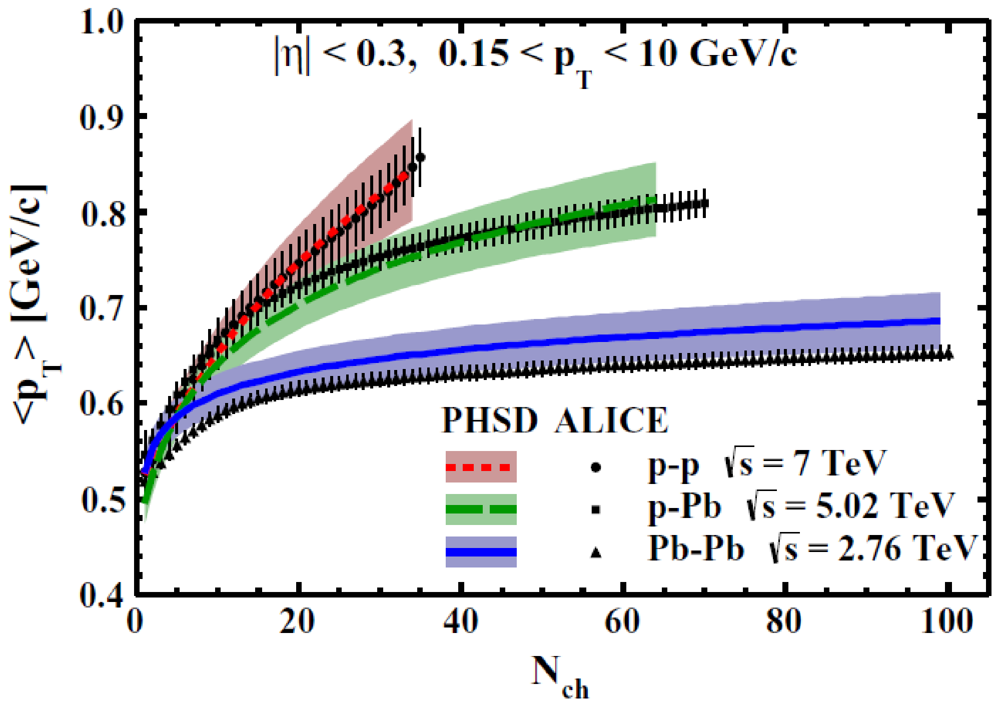


- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

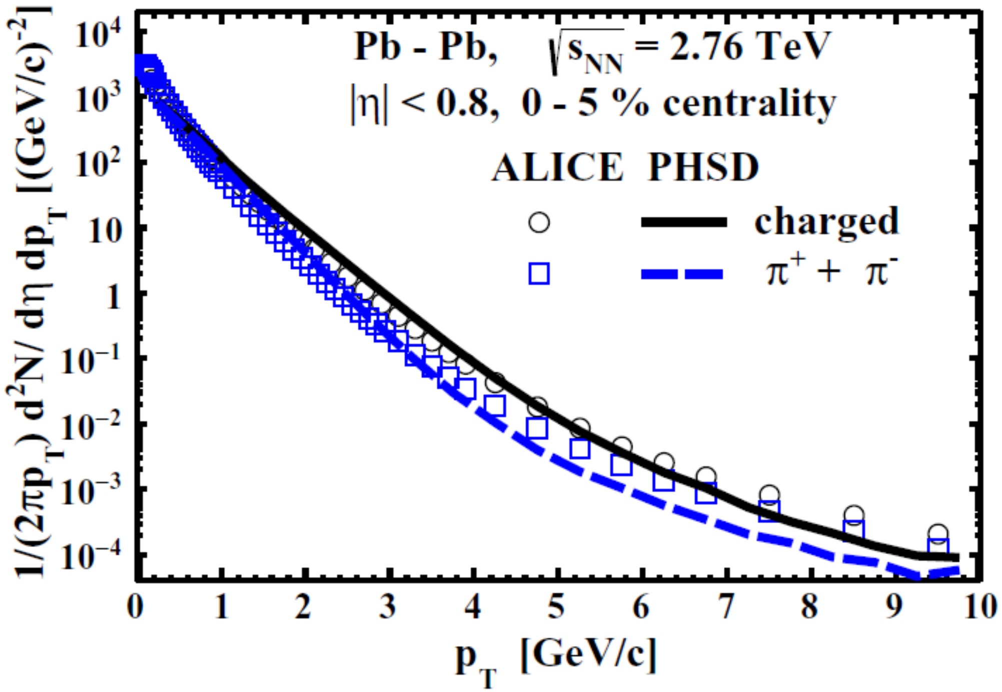
V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

p_T spectra at LHC

Mean p_T of charged hadrons vs N_{ch}
p+p at $s^{1/2}$=7 TeV
p+Pb at $s^{1/2}$=5.02 TeV,
Pb+Pb at $s^{1/2}$=2.76 TeV



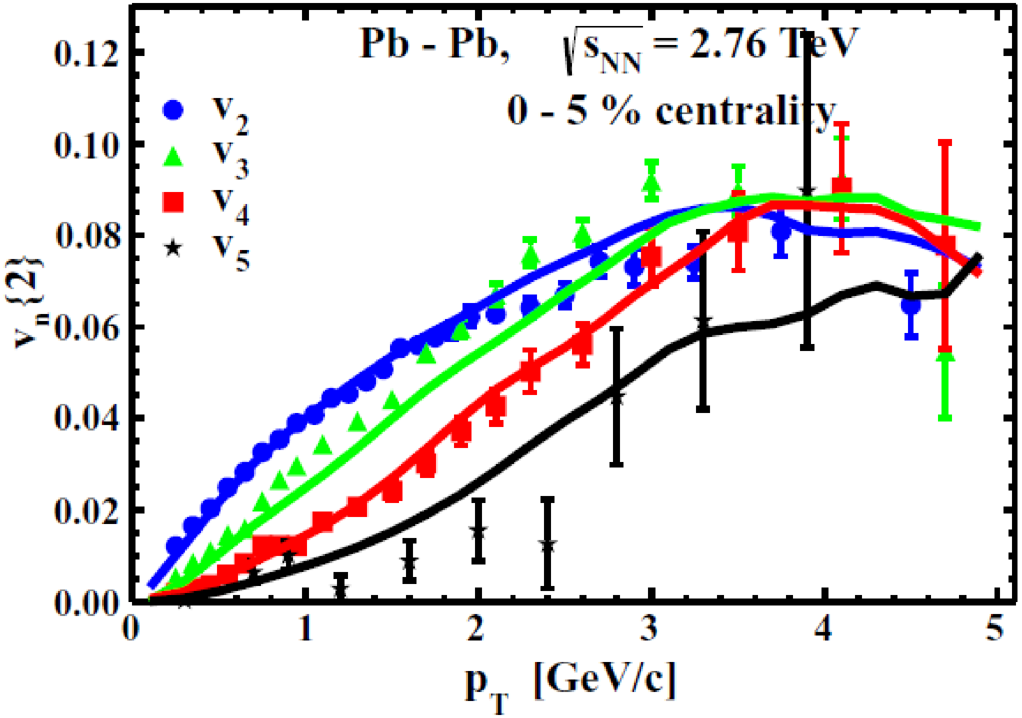
p_T spectra of charged hadrons and pions
central Pb+Pb at $s^{1/2}$=2.76 TeV

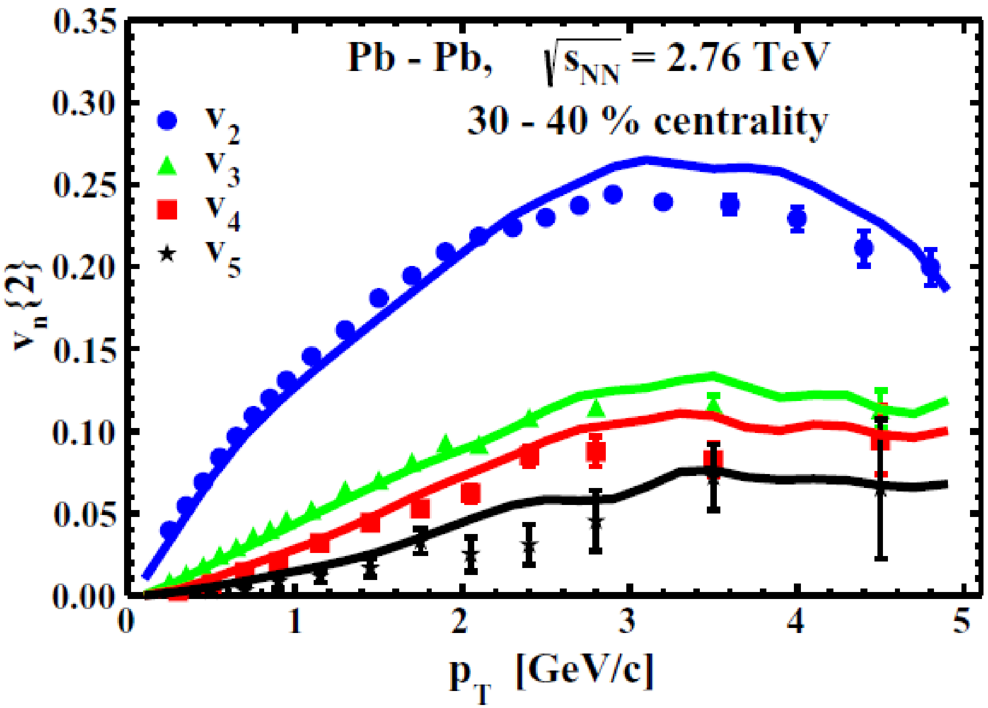


➔ **PHSD reproduces ALICE data**

V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

V_n (n=2,3,4,5) at LHC





symbols – ALICE

PRL 107 (2011) 032301

lines – PHSD

- PHSD: increase of v_n (n=2,3,4,5) with p_T
- v_2 increases with decreasing centrality
- v_n (n=3,4,5) show weak centrality dependence

V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534